DOCTOR OF PHILOSOPHY

Climate change and conservation policy

developing adaptation strategies to minimise climate change impacts to the conservation interest of Scotland's standing freshwaters

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Climate change and conservation policy: developing adaptation strategies to minimise climate change impacts to the conservation interest of Scotland’s standing freshwaters

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Abstract

There is little doubt that anthropogenic climate change will have long lasting, unavoidable, large scale and cross sector effects. Having a clear understanding of the scale and rate of projected future changes, and the potential impacts of those changes at multiple spatial and temporal scales, will be important to allow environmental managers the best chance of adapting to changing conditions. There are particular concerns about impacts on freshwater systems due to the coupling of direct impacts to both hydrology and ecology. Expected changes can be grouped into three functional categories: those affecting physico-chemical (broadly water quality), hydromorphological (physical structure and habitat) and biological elements of the lake system. The Lake-Landscape Context framework provides a way of approaching the sensitivity or resilience of an individual lake to change by exploring the complex and multi-layered relations between water, land and human activity. However, the exact combination of strategies and actions available to environmental managers is yet to be comprehensively documented beyond broad principles. To reach this goal, to manage our ecosystems in the most comprehensive and responsible way, we need to have a clear understanding of what and where that resource is, what the conservation priorities currently are and where threats to these priorities are likely to emerge. Therefore, the overall aim of this thesis was to develop adaptation strategies to minimise climate change impacts on the conservation interests of Scotland's standing freshwater. This was approached through the adoption of the ESVRA conceptual framework, intended to assist policymakers and practitioners in adaptation planning. Practical actions can be guided by working through the framework's four key stages: understanding exposure to the pressure (external drivers); considering the sensitivity and resilience of the system at multiple scales (internal functions); exploring areas of vulnerability (a measure of sensitivity plus exposure); and consideration of multiple possible responses across spatial and temporal scales. Chapter 2 explores the lake resource making use of the latest geospatial data and GIS techniques to investigate Scottish standing freshwaters in depth. 5,165 Scottish lakes exhibit an outstanding myriad of forms and sizes ranging across the country. This variety of form, density and distribution contribute to habitats of international importance for numerous species. Perhaps because of this diversity, no natural grouping of lakes were found based on simple hydromorphological categorisations. The use of landscape and wildness 'scoring' is a

novel geographic approach, which may be an important factor in how landscapes are valued in the future. Chapter 3 investigates the direct exposure to global climate change facing Scotland. Projected changes to global climate were downscaled to illustrate impact on the UK and Scotland using both the UKCP09 and HadGEM2-ES climate models. Climate change by the 2050s will impact the UK in the range 1.1°C to 2.7°C with a clear South-East/North-West gradient. Precipitation too is projected to change in the UK in this time, with annual precipitation varying from -65 to +116 mm/yr. By incorporating the climate model data into a GIS it was possible to further interrogate the results for specific locations, with a detailed water balance model created for all 5165 lakes. This model suggests that during the summer months there will be sustained periods of water scarcity and deficit. Finally, in this chapter, a climate change spatial risk assessment was undertaken, identifying 200 lakes in the area of greatest projected change. Leading on from these findings, Chapter 4 explores the vulnerability of Scotland's standing freshwaters. A vulnerability framework attempts to place resilience as a key part of the model, which has to date been missing from similar assessments. The expert weighted scoring mechanism highlights 851 of Scotland's standing freshwaters, geographically spread across the country, as being highly vulnerable to projected climate changes. The results were mapped to show the vulnerability across Scotland and a display system for individual lakes proposed that allows a transparent and coherent structure that can shed light on distinct components of vulnerability, so that each can be evaluated individually, and in combination. Finally, in Chapter 5, a multipart online survey with key stakeholder experts actively involved in freshwater environmental management was produced to approach adaptation strategies and actions themselves. Over 80 adaptation actions specifically applicable to Scotland's standing freshwaters were collated and grouped into 12 adaptation strategies. All 12 strategies were considered desirable with six strategies considered 'Definitely feasible', a further four considered 'Likely feasible'. This provides a framework of potential actions that could help to reduce system sensitivity by increasing adaptive capacity or system resilience. In conclusion, while there are undoubtedly challenges ahead for Scotland's standing freshwaters and for those who manage them, there is clear opportunity to make proactive and engaged decisions to minimise the impact of climate changes on the conservation interest of these important habitats.

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Author Declaration

I declare that the work recorded in this thesis is my own and is of entirely my own composition. All references cited have been consulted. No part of this thesis has been submitted for another degree.

Elements of the thesis have previously been published in peer-reviewed literature and can be found in Appendix A:

Muir, M. C. A., Spray, C. J., & Rowan, J. S. (2012) Climate change and standing freshwaters: informing adaptation strategies for conservation at multiple scales. *Area*, 44(4), 411–422.

Chapter 1 - General Introduction

1.1 Global climate change

Warming of the global climate system is unequivocal, with global average temperatures having risen by nearly 0.8 ºC since the late 19th century, and rising at about 0.2 ºC/decade over the past 25 years (Bates *et al.* 2008; Jenkins *et al.* 2009). It is very likely that man-made greenhouse gas emissions caused most of the observed temperature rise since the mid-20th century (Bates *et al.* 2008; Steffen 2008; Jiménez Cisneros *et al.* 2014). In the UK the last four decades have each been the warmest on record (Jenkins *et al.* 2009). We are already seeing examples of extreme weather patterns causing sustained periods of drought (Jankowski *et al.* 2006; Burke *et al.* 2010; Falloon & Betts 2010; Jiménez Cisneros *et al.* 2014; Thomas *et al.* 2015) or exceptionally large flooding events (Prudhomme *et al.* 2010; Maltby *et al.* 2011; Garris *et al.* 2015; Watts *et al.* 2015) and while these cannot be conclusively or solely linked to human induced climate change (Falloon & Betts 2010), it is very likely that these events will become more common in the future and will have sustained impacts on our natural environment (European Environment Agency 2012; Jiménez Cisneros *et al.* 2014).

The 5th Assessment report of the International Panel on Climate Change report (IPCC AR5), written by over 900 of the world's top climate scientists, was published in 2014 and leaves no doubt that anthropogenic climate change will have long lasting, unavoidable, large scale and cross sector effects (Jiménez Cisneros *et al.* 2014). IPCC AR5 reports 'strong evidence' of impacts of recent change already visible across physical, biological and human systems. Rising temperatures and changing precipitation patterns are already associated with changes to both ecosystem function and composition across terrestrial, freshwater and marine ecosystems (Dudgeon *et al.* 2006; Jeppesen *et al.* 2010; Steudel *et al.* 2012; Turnbull *et al.* 2013; Tomimatsu *et al.* 2013; Albouy *et al.* 2014; Berry *et al.* 2015). Having a clear understanding of the scale and rate of projected future changes, and the potential impacts of those changes at multiple spatial and temporal scales, will be important to allow environmental managers the best chance of adapting to changing conditions (Munang *et al.*

2010; Keppel & Wardell-Johnson 2012; Wilby & Wood 2012; Cook *et al.* 2012; Fabricius & Cundill 2014).

In preparation for the IPCC AR5 launch, outputs of the Coupled Model Intercomparison Project (CMIP5) climate models have recently been made available via WORLDCLIM (Hijmans et al. 2005). This data set is downscaled from a global circulation model (GCM) to a 30 second arc (approximately 1km^2) resolution. These models are run on four globally agreed representative concentration pathways (RCPs) developed for, but independently of, IPCC AR5 (Moss *et al.* 2008; Collins *et al.* 2011; Jones *et al.* 2011). The concentration pathways describe four realistically possible climate futures (Jones *et al.* 2011) based directly on projected concentrations of CO_2 found in the upper atmosphere, rather than emissions scenarios as before (Moss *et al.* 2008). The four RCPs: RCP2.6, RCP4.5, RCP6, and RCP8.5, are named after the possible range of radiative forcing values in the year 2100 relative to pre-industrial values (+2.6, +4.5, +6.0, and +8.5 W/m2, respectively; see Figure 1.1).

The CMIP5 models provide global data for use by specialist climate modellers. However, there is a need for downscaled regional models for use by wider audiences (del Barrio *et al.* 2006; Tabor & Williams 2010; McClure *et al.* 2013). One such approach, the UKCP09 model, is aimed at engaging stakeholders from diverse backgrounds to approach adaptation in the UK (UKCP 2009). UKCP09 is a downscaled regional climate model based on older CMIP4 climate models used for IPCC AR4. UKCP09 data provides climate projections at a 25km^2 spatial resolution, over multiple timescales and three emissions scenarios. A key feature of UKCP09 is that it is able to quantify uncertainty by assigning each outcome a related probability by running multiple scenarios with multiple model inputs prior to user query (Street *et al.* 2009). The utility of UKCP09 has led to it being widely used in a range of sectors for UK based climate related studies (Duncan *et al.* 2010; Jaroszweski *et al.* 2010; Burke *et al.* 2010; Prudhomme *et al.* 2010; Cloke *et al.* 2010; Rennie & Hansom 2011). The probability based output has been credited with allowing stakeholders to plan for a wide range of outcomes due to its complexity thus allowing a robust and in depth understanding of the wide range of projected changes. However, this complexity has also been criticised as making the output too wide and unfocussed for the majority of users (Watts *et al.* 2015).

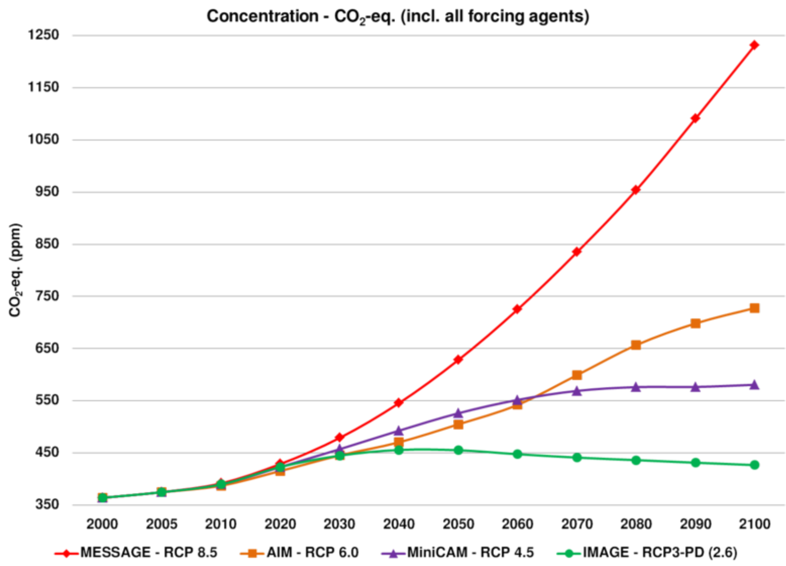


Figure 1.1 - Representative concentration pathways (RCPs) used as basis for CMIP5 global climate model projections for IPCC AR5. From Moss *et al*. 2008.

In addition to future drivers of change causing potentially wide ranging projections, further problems are caused by inter-annual climate variation, which is difficult to accurately model (Tabor & Williams 2010). Both of the models described here are looking at long term, 30-50 year averages of observed data to produce 30-year temporal trends for climate projections. These average trends are important and provide a starting point for understanding the scale of projected change (Jiménez Cisneros *et al.* 2014; Daron *et al.* 2015). However, the change in long term average conditions often occurs as a result of changes in the frequency, intensity, or duration of extreme weather and climate events (Burke *et al.* 2010; Falloon & Betts 2010). Within and between year variation is likely to see larger extremes than modelled in the long term trends. Figure 1.2 presents UK mean monthly temperatures for January and July from 1910 – 2011. The variation around the linear average increase is immediately obvious when seen in this form. This is important to note as both hydrological and ecological systems are likely to be strongly stressed by the extremes (Winder & Schindler 2004b; Adrian *et al.* 2009; Arvola *et al.* 2010). It is the extremes that place excessive and often unexpected demands on ecological systems which may lack the adaptive capacity or resilience to deal with those extremes (Williams *et al.* 2008; Bellard *et al.* 2012; Jiménez Cisneros *et al.* 2014; Watts *et al.* 2015). Adaptation management strategies will need to aim to build both adaptive capacity to cope with long term change and resilience to cope with short term extremes (Brooks *et al.* 2005; Smit & Wandel 2006; Munang *et al.* 2010; Hill & Engle 2013).

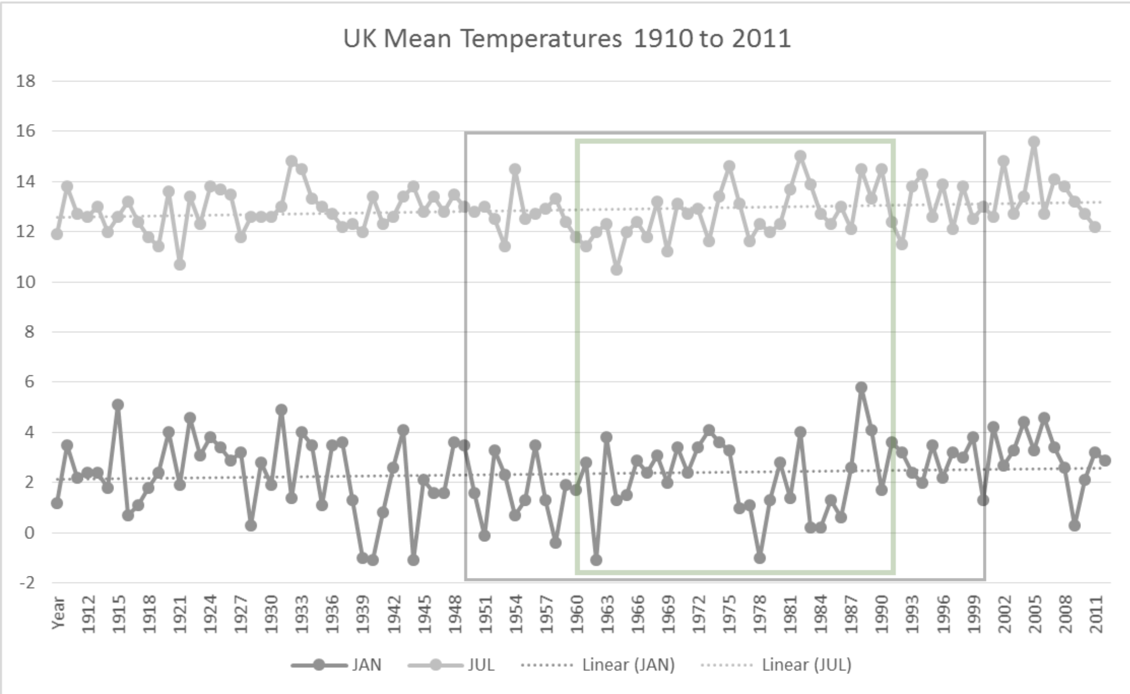


Figure 1.2 - 100 years of climate data for the UK showing mean January and July temperatures from 1910 – 2011 (Data sourced from UK Met Office). The linear trend shows a general increase over this time period but the variability is high (Linear fit R^2 Jan = 0.0082; July = 0.033). The boxes show the baseline periods used by two climate models used in this thesis – HadGEM2-ES 1950-2000; UKCP09 1961-90.

1.2 Climate change impacts to ecohydrology of standing freshwaters

Global climate change is predicted to be a major cause of change across all ecosystems and there are particular concerns about impacts on freshwater systems due to the coupling of direct impacts to both hydrology and ecology (Bates *et al.* 2008; Woodward *et al.* 2010; Wilby *et al.* 2010). Ecohydrology, or hydroecology, is a relatively new interdisciplinary research area (Hannah *et al.* 2004; Wood *et al.* 2007; Jackson *et al.* 2009; Manfreda *et al.* 2010) operating at the interface of the more traditional disciplines of hydrology and ecology. There have been numerous calls for greater understanding and investigation of these links and the relation between the two, particularly with reference to changing climate (Hannah *et al.* 2007; Vaughan *et al.* 2009; Vaughan & Ormerod 2010; Wilby *et al.*

2010). Predicting how standing freshwater systems, and ecological interests in particular, will respond to climate driven changes greatly amplifies uncertainties already implicit in their environmental management (Moss 2014; Watts *et al.* 2015).

Climate change is likely to affect the hydrological cycle most significantly through altered temperature and precipitation patterns, intensities and extremes (Bates *et al.* 2008; Whitehead *et al.* 2009; Johnson *et al.* 2009; Kreyling *et al.* 2014; Moss 2014). This will impact the ecology of standing freshwaters through multiple pathways, acting at different geographical scales and in response to landscape setting (Soranno *et al.* 2009; Wagner *et al.* 2011; Garris *et al.* 2015). Expected changes can be grouped into three functional categories: those affecting physico-chemical (broadly water quality), hydromorphological (physical structure and habitat) and biological elements of the lake system (see Table 1.1). There are problems with attributing changes solely to climate, as lake systems are commonly affected by multiple interacting stressors (Strayer 2010; Hadley *et al.* 2012; Steudel *et al.* 2012). In Scotland, for example, other key stressors include water level management for hydropower generation, land use management - with intensive farming practices leading to eutrophication - and acidification from atmospheric deposition of industrially-derived emissions (Bennion *et al.* 2004; McFarland *et al.* 2010; Maltby *et al.* 2011; Korosi & Smol 2012). These, and similar issues, are themselves subject to other drivers including EU Common Agricultural Policy reforms and carbon emission controls (Wilby *et al.* 2006; Bates *et al.* 2008; Cizková *et al.* 2011; European Environment Agency 2012).

Ecological responses to changing climate have been well documented in a broad range of species, predominantly in terms of range movements (Pearson & Dawson 2003; Araújo *et al.* 2006; Lawler *et al.* 2013; Burrows *et al.* 2014), phenological changes (Winder & Schindler 2004b; Thackeray *et al.* 2010; Dijkstra *et al.* 2011; Moyes *et al.* 2011; Bellard *et al.* 2012; Chapman 2013) and more recently through population plasticity and genetic adaptation (Hof *et al.* 2011; Muir *et al.* 2013, 2014; Pratt & Mooney 2013; Baudron *et al.* 2014). The same changes will affect habitats too, though the responses are more complex to unravel (Loehle 2011; Garris *et al.* 2015). In addition to direct effects on habitat quality, climate change will lead to various indirect impacts. For example it could enable greater movement of species (both native and invasive non-natives) altering competitive dominance, increasing predation rates and enhancing the virulence of disease (Rahel & Olden 2008; Matthews &

Marsh-Matthews 2011; Chapman 2013). This can irredeemably alter system function, paving the way for further changes and increasing uncertainty with potential ‘invasion pathways’ through the landscape (Hellmann *et al.* 2008; Vicente *et al.* 2013). Dependant on local circumstances, management practices could range from complete eradication to tolerance and even consideration of the 'new' species as part of a ‘novel community’ - an enrichment of local biodiversity or a key element in maintaining or developing ecosystem services (Walther *et al.* 2009; Webber & Scott 2012).

One of the greatest challenges for climate change adaptation studies is the uncertain response of habitats to change (Pearson & Dawson 2003; Phillips *et al.* 2006; Huntley *et al.* 2012). While some species may move, others may be bound to certain locations due to abiotic factors (Warren & Bradford 2014). Standing freshwaters, static bodies within the landscape in which they were formed, are one such habitat where the ability to move with a shifting climate envelope is severely limited. While some species which utilise the lakes may be able to move, particularly those with high dispersal ability like birds, the lake itself and potentially some of the less mobile species cannot (Huntley *et al.* 2012; Lawler *et al.* 2013; Burrows *et al.* 2014). This may lead to cases of trophic asynchrony and functional change, which could have a significantly negative effect on the conservation value of these habitats (Oliver & Morecroft 2014). Subsequently, this increases the challenge of developing adaptation strategies and management targets (Ormerod 2009; Pittock *et al.* 2009, Kernan *et al*. 2010).

Table 1.1 -Expected impact of climate changes to physico-chemical, hydromorphological and biological functioning of standing freshwaters

Physico-chemical changes *Water temperature; mixing/stratification; dissolved oxygen; carbon flux; nutrient loading; alkalinity/acidity; photic environment.*	Expected physico-chemical changes will include increased water temperatures (particularly in the epilimnion), including less frequent ice-cover and earlier snowmelts (Bates *et al.* 2008; Feuchtmayr *et al.* 2011; Davis *et al.* 2013). Related consequences include earlier onset and longer periods of thermal stratification, potentially modifying dissolved oxygen and carbon levels, as well as increasing the release of sediment-bound nutrients and contaminants into the water column (Jankowski *et al.* 2006). These changes to water chemistry may lead to increases in cyanobacterial blooms, for example, which will alter the photic environment and ecological function of the whole system (Jeppesen *et al.* 2005; Carvalho *et al.* 2012; Spears *et al.* 2013; Maileht *et al.* 2013).
Hydromorphological changes *Hydrological regime (amount and timing of flow); retention time; sediment changes; shoreline complexity; connectivity; habitat structure.*	Changes in precipitation amounts and timings, resulting in more extreme floods and droughts, will alter surface and groundwater flows (Bell *et al.* 2007; Kong *et al.* 2010; Prudhomme *et al.* 2012; Watts *et al.* 2015). Variability is likely to increase, affecting hydraulic retention times as well as sediment transport and nutrient loading (Jeppesen *et al.* 2005, 2007; Vaughan & Ormerod 2010). Changes to the water-level regime (Wantzen *et al.* 2008) will have consequences for lake–landscape connectivity and will result in changes to shoreline complexity and habitat structure (Abrahams 2008; Hermoso *et al.* 2012; Warfe *et al.* 2013).
Biological changes *Productivity; phenology; trophic structure; species composition; invasive non-native species.*	Interactions between climate change and lake biology are complex because other factors such as stochastic phenology, resource availability, density dependence and predation may control the abundance, distribution and size of the biota (Adrian *et al.* 2009; Heino *et al.* 2009; Feuchtmayr *et al.* 2011). Furthermore, these factors will operate at different geographical and temporal scales. Responses are often species-specific and vary between sites (Pratt & Mooney 2013). Freshwater systems have already been shown to be undergoing changes in composition, organism abundance and productivity, and considerable evidence is already available showing phenological shifts in relation to earlier season warming potentially leading to trophic asynchrony (Winder & Schindler 2004a; b, Thackeray *et al.* 2010, 2011). Species ranges are documented to be changing, with species 'climate envelopes' (the geographic ranges with conditions suitable for species survival) (Pearson & Dawson 2003; Dawson *et al.* 2003; Araújo *et al.* 2006; Loehle 2011) showing latitudinal moves North and South, or up altitudinal gradients depending on thermal proclivity (Thomas *et al.* 2006; Bennie *et al.* 2013; McDowell *et al.* 2014).

The impacts of climate change, both direct and indirect, will be felt at multiple scales, within and between systems. Building on an increasing interest in applying landscape ecology to 'waterscapes' or landscape limnology (Webster *et al.* 1996; Wiens 2002; Galbraith & Burns 2007), the related concept of the scaling relationships between lakes and their surrounding environment, the Lake-Landscape Context framework (Soranno *et al.* 2009; Figure 1.3), provides a way of approaching the sensitivity or resilience of an individual lake to change by exploring the complex and multi-layered relations between water, land and human activity. Rowan (2010) extends this concept with a hierarchical description of the scales and linkages that control the hydromorphological, physico- chemical, and biological character of lake systems in the UK (Figure 1.4).

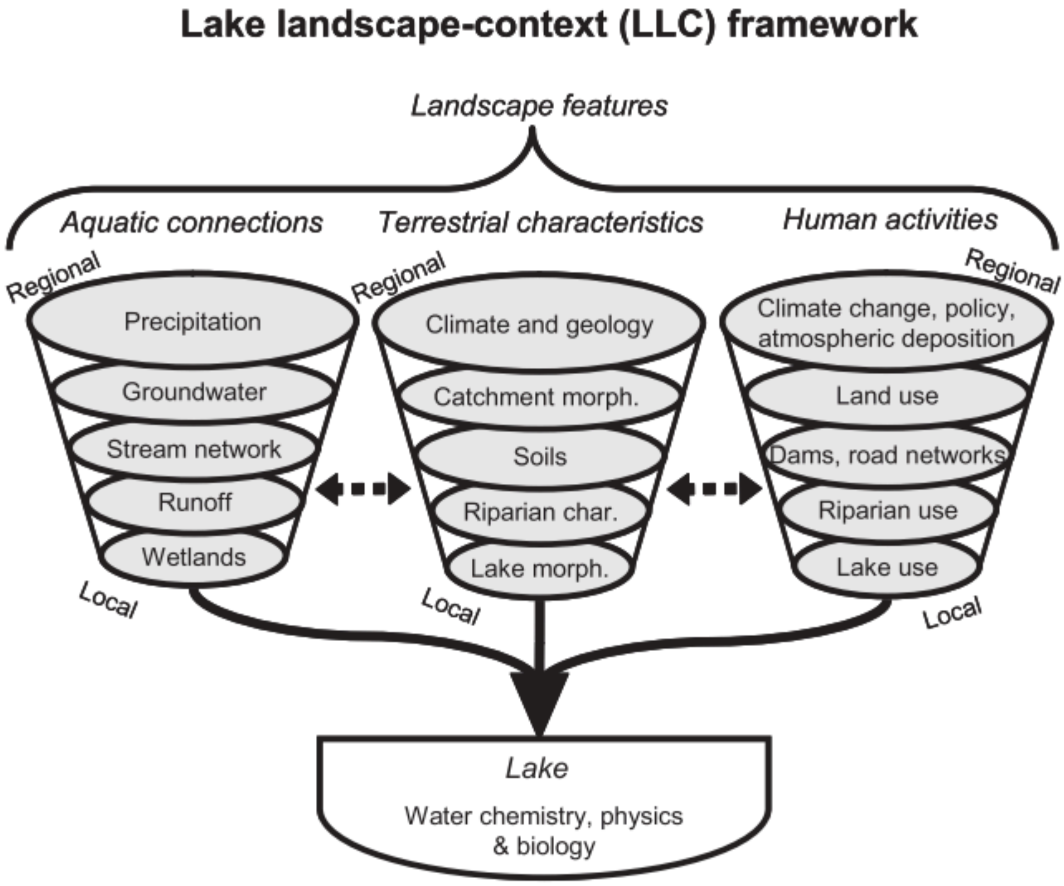


Figure 1.3 - The lake landscape-context framework: linking aquatic connections, terrestrial features and human effects at multiple spatial scales (from Soranno *et al.* 2009).

↑ Regional influences — SCALE — Increasingly site specific ↓

Scale	Hydro-climatic	Terrestrial	Biotic	Human
Ecoregion	• Latitude/longitude • Solar radiation regime • Temperature • Precipitation • Wind regime	• Geological structure and lithology • Physiography • Soils	• Regional biomes • Biomass • Phenology	• Airborne pollution • Climate change
Landscape setting	• Continentality • Orographic effects • Environ. lapse rates • Runoff quantity and timing • Ice cover	• Elevation • Topographic variation • Drainage network and density • Glacial history	• Habitat diversity • Species dispersal • Flux of humic substances	• Economy • Demographics • Land cover and management • Water resource management
Catchment-lake relation	• Hydrological regime • Hydrological pathways • Surface:groundwater contribution	• Hydrogeology • Groundwater and solute flux • Sediment budget • Salinity	• Biological continuity • Nutrient cycling • Acidity	• Impoundments • Water transfers • Drainage • Land management • Riparian land cover
Lake hydromorphology (water body scale)	• Size and shape • Stratification and mixing depth • Water residence time • Resuspension and internal loading	• Shoreline complexity • Littoral:pelagic ratio • Riparian habitat structure	• Appropriate species composition • Integrity of trophic function • Alien species	• Water level manipulation • Cumulative pressures and disturbance
Meso-habitat patches	• Microclimate • Exposure • Erosion/sedimentation	• Littoral slope • Substrate • Wave energy	• Local carbon flux • Pollution • Habitat patches	• Local pressures to shore and lake bed

Figure 1.4 - A WFD compliant eco-geomorphic framework for contextualising UK lakes (from Rowan 2010)

This framework moves us towards understanding that lakes formed in similar ways, located in similar conditions with similar catchment relations are likely to function in similar ways (Kernan *et al.* 2002; Galbraith & Burns 2007; Weijters *et al.* 2009; Staehr *et al.* 2012). Small shallow lakes situated within a large catchment (characteristic of South East Scotland) are likely to respond differently to large deep lakes (typical of North West Scotland). The former may be sensitive to reduced summer precipitation, with lower runoff reducing the flushing of the system and increasing residence times. This may lead to greater accumulation of phosphorus in sediments (as shown by Spears *et al.* 2011 for Loch Leven) which, when periodically released from storage can cause cyanobacterial blooms (Elliot 2011; Carvalho *et al.* 2012; Spears *et al.* 2013). By contrast, a large deep lake is less likely to respond to these drivers of change, but may be more sensitive to other changes such as longer periods of thermal stratification reaching greater depth leading to deoxygenation of the hypolimnion and stressed fish assemblages (Arvola *et al.* 2010; Mooij *et al.* 2010; North *et al.* 2014). The importance of the lake landscape context also extends to lakes with similar intrinsic characteristics (e.g. surface area, mean depth, alkalinity) but different catchment characteristics (size, vegetation cover or land use) that will likely respond differently to change (Webster *et al.* 1996; Soulsby *et al.* 2002; Galbraith & Burns 2007). These differences cause a challenge for conservation where the responsible organisations must manage landscapes composed of many thousands of individual ecosystems, most often with limited data or resources to support interventions (Soranno *et al.* 2010; Woodward *et al.* 2010).

1.3 Conservation and the adaptation challenge

Ecosystems globally are under increasing stress and governance systems are failing to protect our natural environment (Fuller *et al.* 2010; Watson *et al.* 2011; Tingley *et al.* 2013; Doak *et al.* 2013; Heller & Hobbs 2014). Conservation of our current natural resources alone is a major challenge, international targets are regularly being missed and species are being driven to extinction while habitats decline in quality (Brooks *et al.* 2006; Rahel *et al.* 2008; Crossman *et al.* 2012; Berry *et al.* 2013; Whitehead *et al.* 2014). As climate change impacts grow these challenges are very likely to become much greater at all scales (Bellard *et al.* 2012; Berger *et al.* 2014; Watts *et al.* 2015).

A range of methods have been utilised to protect freshwater habitats and species including legislation, economic instruments, campaigning, research and site designation (Heller & Zavaleta 2009; Chessman 2013; Doak *et al.* 2013). Whatever the balance of actions, projected changes in climate present a new set of challenges with potential impacts across the standing water resource base (Mooij *et al.* 2005; Adrian *et al.* 2009; Jackson 2011). In this context, there is a need to review how we plan to protect the conservation interests of freshwater sites (Sutherland *et al.* 2010). This is especially important in the face of other changing lake and catchment pressures – which include diffuse pollutants, morphological modification, recreation and invasive species (Johnson *et al.* 2009; Maltby *et al.* 2011).

While many conservation efforts continue to focus on single species ‘flagship’ style approaches as catalyst for wider habitat protection (Simberloff 1998; Miller *et al.* 2012; Heller & Hobbs 2014) proponents of conservation strategies dealing with uncertain future change have argued for a more holistic approach (Schwenk & Donovan 2011; Higgins *et al.*

2012; McKenzie *et al.* 2013). Such an approach argues for the need to re-naturalise and re-connect systems (Rahel 2007; Arponen *et al.* 2012), to provide corridors to enable species movement in the face of change (Rahel *et al.* 2008; Lawler *et al.* 2013; Lacher & Wilkerson 2014) and to act at the landscape rather than site scale (Soranno *et al.* 2010; Schwenk & Donovan 2011; Higgins *et al.* 2012; Mazziotta *et al.* 2014). Management at this wider scale has been advocated by the recent growth of the concept of ecosystem services which recognises the multiple values inherent in our natural environment (van de Sind 2012; Mace *et al.* 2012; Mastrangelo *et al.* 2013; Iverson *et al.* 2014; Harrison *et al.* 2014). Figure 1.5 illustrates a selection of the freshwater ecosystem services in the UK based around the concept of provisioning, regulating, supporting and cultural services (Maltby *et al.* 2011). The increasing importance of the concept of ecosystem based adaptation (EBA) can be argued to be a direct result of this discourse (Cook & Spray 2012; Iacob *et al.* 2014; Iverson *et al.* 2014) and offers further encouragement to those aiming to integrate management actions at multiple scales across sectors (Wilby *et al.* 2010; Doswald *et al.* 2014; Burch *et al.* 2014).

Table 9.1 Ecosystem services provided by the Freshwater Broad Habitat. Component and sub-component habitats potentially delivering ecosystem services are river (R), lake (L), pond (P), grazing marsh (GM), reedbed (RB), fen (F), and Lowland raised bog (LRB).

Final services of Freshwater habitat	Habitats potentially delivering services							Conditions or characteristics of habitats required
	R	L	P	GM	RB	F	LRB	
Provisioning								
Fish	•	•	•	•				Commercially significant fisheries (crayfish, salmon, trout) based on rivers, lakes and ponds in suitable conditions.
Dairy and beef				•		•		Wetland grasses provide grazing, silage and hay, nutrition level depends upon management.
Reeds, osiers and watercress	•	•	•	•	•	•		Reeds grow in saturated soils and slow flowing or still water up to 0.3 m deep. Osiers produce withies for basket making; requiring saturated soil conditions. Cress-beds need swiftly flowing high pH clean water.
Water	•	•	•		•	•		Open water habitats provide a water source for public supply, irrigated crops, power station cooling, industrial processing and fish farming, but high evaporation rates may suppress total water availability.
Peat		•	•	•	•	•	•	Peat provides the basis of some composts for horticulture. Peat needs to be >0.5 m deep to be commercially exploitable due to recent planning guidance.
Navigation	•	•						Navigable waterways need sufficient water depth and low velocity.
Health products	•	•	•			•		Mineral spas, medicinal plants (e.g. bogbean), medical leeches.
Regulating								
Carbon regulation		•	•	•	•	•	•	Carbon accumulates where production of plant litter exceeds decomposition and generally under waterlogged, predominantly anaerobic conditions. Deposition of organic sediments within lakes, ponds and reservoirs is an important component of the carbon budget.
Flood regulation	•	•	•	•	•	•		Flood reduction relies on available water storage. Permanently saturated habitats with no storage may generate or augment floods.
Flow regulation	•	•	•	•	•	•	•	River flow, groundwater recharge influenced by landscape location, water storage characteristics and connection with other water bodies.
Water quality regulation	•	•	•	•	•	•		Freshwater systems can dilute, store and detoxify waste products and pollutants, however there are threshold levels and some systems may accumulate substances to toxic levels.
Local climate regulation	•	•	•	•	•	•	•	Temperature and humidity may be different within the habitat and without; degree depends on size. Important moist microclimates can develop.
Fire regulation	•	•	•	•	•			Open water bodies can act as natural fire breaks.
Human health regulation	•	•	•	•	•	•	•	Natural freshwater systems can increase well-being and quality of life if visually attractive and supportive of physical recreation. Mismanaged freshwaters can be sources of water borne diseases and disease vectors (e.g. mosquitoes), but also sources of biocontrol agents.
Cultural								
Science and education		•	•	•	•	•	•	Lake, floodplain and mire sediment sequences contain palaeo-environmental archives and human (pre)history, artefacts; that may be lost if disturbed or desiccated. Freshwater ecosystems are important outdoor laboratories.
Religion	•					•		Freshwaters are sites of historical baptism and religious festivals.
Tourism and recreation	•	•	•	•	•	•	•	Extensive recreational fisheries (game species and coarse fisheries depend on good habitat). Tourism depends on landscape appeal and iconic species, such as rare birds, flowers or amphibians. Good water quality and visual appearance required for natural swimming and boating.
Sense of place	•	•	•	•	•	•	•	Water is important in defining specific landscape character and features strongly in art and local culture. Literary and cultural identities embodied in distinctive landscapes such as Snowdonia, the Lake District, the Somerset Levels, Gwent Levels or the Norfolk Broads.
History	•	•	•	•	•	•	•	Freshwaters and especially wetlands have played a key role in human history and settlement since prehistoric times Water is a recurrent feature at the heart of many historically important places, battlefields, territorial boundaries and many local folklore connections.
Supporting services								
Biodiversity	•	•	•	•	•	•	•	All freshwater habitats with open water: species depend on conditions such as, temperature, oxygen level, depth and velocity of water and area with suitable conditions. Some habitats may provide temporary habitat for fish (e.g. for spawning), such as floodplains.

Figure 1.5 – Ecosystem services provided by broad freshwater habitat types covering the key provisioning, regulating, cultural and supporting services (from Maltby *et al*. 2011)

The potential for adaptation to be incorporated into environmental policy is, however, dependent on the underlying philosophy of environmental managers, the political will and timescale in which decisions can be made and funding put in place (Lemieux & Scott 2011). Figure 1.6 shows one conceptualisation of this idea – the adaptation continuum – with approaches ranging from conservatively offering no investment in adaptation, to an acceptance of predicted future conditions and willingness to engage in transformational policy (Walker *et al.* 2004; Folke *et al.* 2010; Oliver & Morecroft 2014). The likelihood is that as pressures continue to rise, management actions will move from left to right along the continuum. The evidence provided thus far establishes that doing nothing is not a viable option, but the exact combination of strategies and actions available to environmental managers is yet to be comprehensively documented beyond broad principles (Hopkins *et al.* 2007; Smithers *et al.* 2008; Morecroft *et al.* 2012; Wilby & Wood 2012; Ausden 2014).

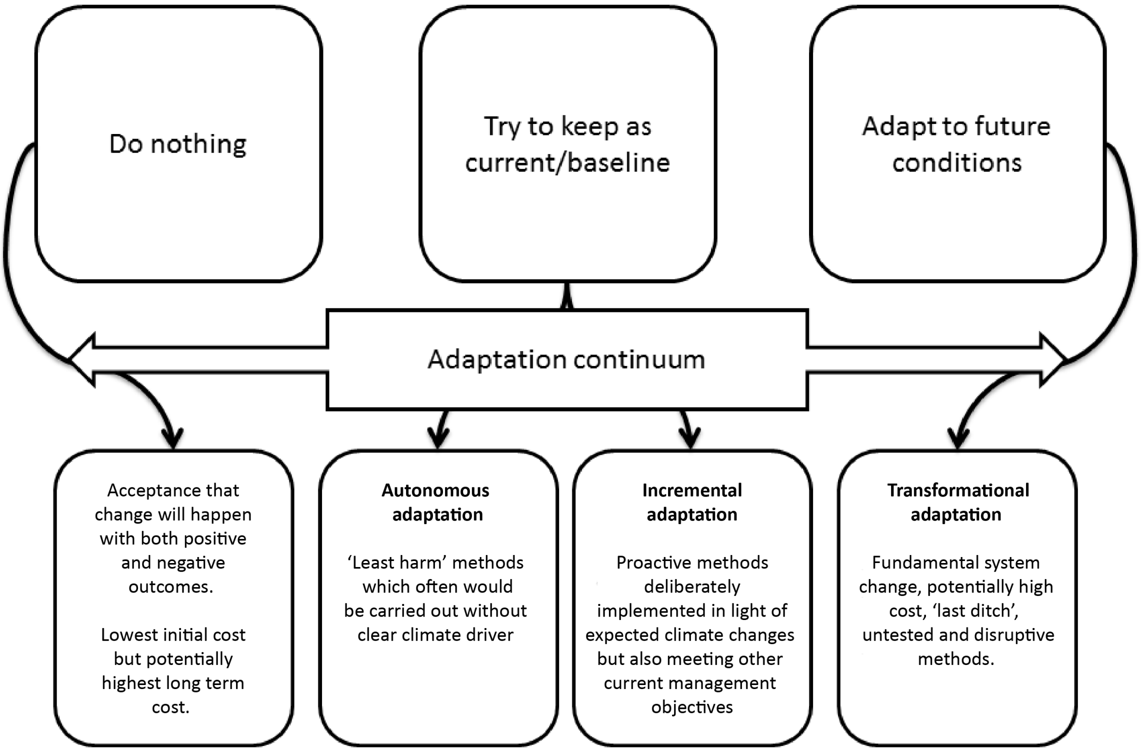


Figure 1.6 – The adaptation continuum – multiple possible options for environmental policy ranging from complete lack of action to transformational system disrupting strategies (after Muir *et al.* 2012)

The need for adaptation strategies and actions beyond broad principles has been well documented (Wilby *et al.* 2010; Hall & Murphy 2011; Mawdsley 2011; Game *et al.* 2011). To date progress towards this goal has been limited and difficult to achieve with so much variety of system form and function. Studies have either been focussed very broadly in terms of conservation adaptation (Wilby *et al.* 2010; Watson *et al.* 2011; Mawdsley 2011; Burch *et al.* 2014) or very specifically in terms of single site plans (Dea *et al.* 2004; Ippolito *et al.* 2010; Ausden 2014). There is a clear need for adaptation strategies at a scale relevant to policy makers and with a focus on a discreet system of interest offering insight across multiple scales from site to national level policy (Soranno *et al.* 2010; Wilby *et al.* 2010; Hill & Engle 2013). To reach this goal, to manage our ecosystems in the most comprehensive and responsible way, we need to have a clear understanding of what and where that resource is, what the conservation priorities currently are and where threats to these priorities are likely to emerge (Cook *et al.* 2013). This thesis aims to meet this need for standing freshwaters in Scotland.

1.4 Study system

Scotland is a relatively small (c. 79,000 km^2), northern maritime state on the Atlantic margins of North Western Europe. It shares a border with England to the south and is bounded by the North Sea to the east, the Atlantic Ocean to the north and west, and the North Channel and Irish Sea to the southwest. In addition to the mainland, Scotland is made up of more than 790 islands including the Northern Isles of Orkney and Shetland and the Inner and Outer Hebrides. Scotland is well known for the variability of its weather. Its position in the mid-latitude westerly wind belt on the edge of the Atlantic Ocean with its relatively warm waters, including the influence of the Gulf Stream, yet close to the continental influences of mainland Europe plays a major role in this. Changes in topography and land use over relatively short distances, together with a long coastline and numerous islands, all add to the variety. The MET Office (www.metoffice.gov.uk/climate) describe three distinct climatic zones in Scotland – Western, Eastern and Northern Scotland. The climate of Western Scotland is wetter and milder than that of Eastern Scotland due to the stronger maritime influence.

The population stands at 5.3 million people, mostly concentrated in the densely urban central belt but populated at low levels through the full extent of the mainland and islands. A number of organisations are directly involved with environmental management of standing freshwaters in Scotland. Legislative and statutory responsibility is devolved to Scottish Parliament and managed by Scottish Natural Heritage (SNH) and the Scottish Environment Protection Agency (SEPA). Scottish Water, a publicly owned company, is the public provider of water for drinking and waste management in Scotland. Many environmental NGO's operate in Scotland with a number, including the Royal Society for the Protection of Birds (RSPB) and the Scottish Wildlife Trust (SWT) in particular, owning and operating a large network of reserves many of which include standing freshwaters.

With over 25,000 lakes and ponds with surface areas greater than 0.1 ha (Hughes *et al.* 2004), standing freshwaters are an iconic part of Scotland's landscape, and represent over 70% of the surface area and 90% of the freshwater volume of Great Britain (Lyle and Smith 1994; Maltby *et al.* 2011). The many different forms and sizes of lakes contribute outstanding geodiversity, as well as habitats of international importance for numerous species of conservation interest (Lyle and Smith 1994, SNH 2003). This variety, and the particular catchment and landscape settings within which these lakes are situated, provide added challenges for conservation management (Galbraith & Burns 2007; Garris *et al.* 2015). As elsewhere, there is little comprehensive data covering the ecology of all these water bodies, or the bio-physical processes that support ecosystem functioning, with particular gaps in knowledge relating to the distribution of physical types, current conditions and the legacy of historical impacts on biodiversity patterns and trends (Rowan *et al.,* 2012).

1.5 Research framework & key terms

Operating at a national scale with a wide ranging and highly variable resource, it was considered important to create a conceptual framework to inform and guide this research project (Thompson *et al.* 2014; Pooley *et al.* 2014). This framework is based on an understanding of the complexities of climate projections and resultant hydrological and ecological changes and is rooted in the adaptive management paradigm (Füssel 2007; Bierwagen *et al.* 2008; Fabricius & Cundill 2014). Whilst this study has its origins in Scotland, the framework should be applicable to climate change adaptation studies across Europe and beyond.

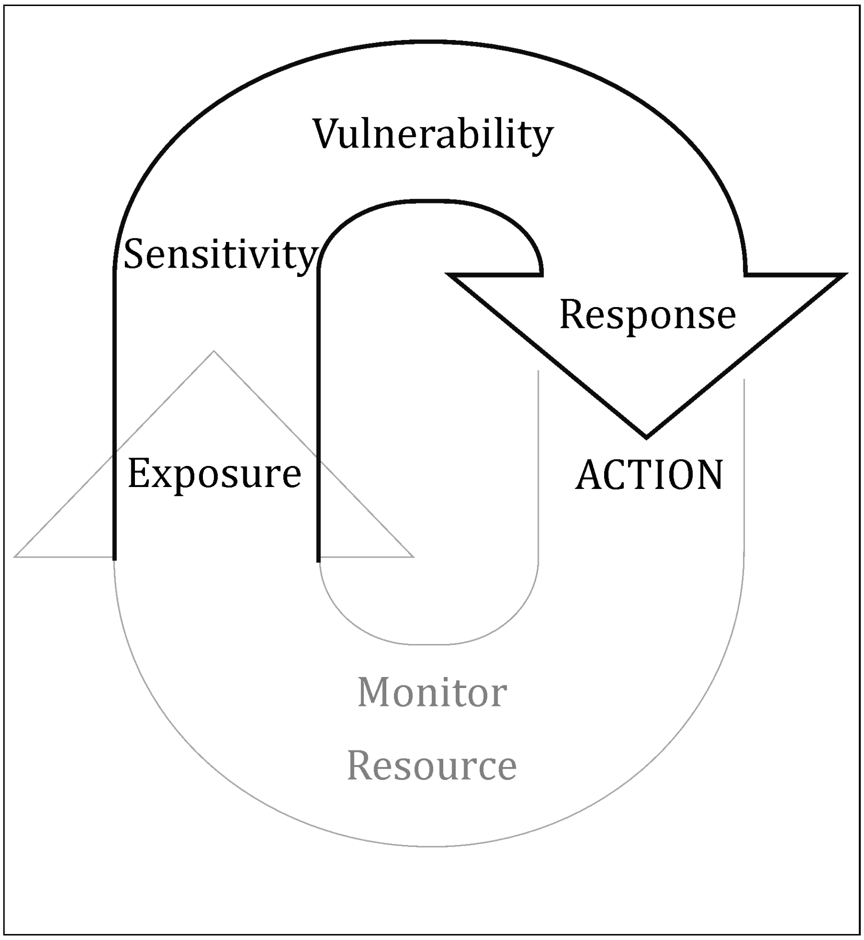


Figure 1.7 – ESVRA framework for climate change adaptation studies (Muir et al., 2012)

The ESVRA conceptual framework, as presented in Figure 1.7, is intended to assist policymakers and practitioners in adaptation planning in the conservation interest. Practical actions can be guided by working through the framework's four key stages:

- understanding exposure to the pressure (external drivers);
- considering the sensitivity of the system at multiple scales (internal functions);
- exploring areas of vulnerability (a measure of sensitivity plus exposure); and
- consideration of multiple possible responses across spatial and temporal scales.

Here, elements of the framework are explored in turn to guide adaptation strategies and actions to minimise the impacts of climate change on the conservation interest of Scotland's standing freshwaters. Identified actions should be monitored and adaptively managed to ensure continued relevance and success (Tompkins & Adger 2004; Bierwagen *et al.* 2008; Fabricius & Cundill 2014).

Due to the often interdisciplinary nature of climate change research a major criticism of many studies has been the lack of coherence around key terminology used, with the resulting danger of misunderstanding and misrepresentation (Gallopín 2006; Smit & Wandel 2006; Hinkel 2011). To avoid such confusion the key terminology used throughout this thesis is presented in Figure 1.8, as defined by the IPCC AR5 WGII Glossary (Agard *et al.* 2014).

Adaptation
The process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate harm or exploit beneficial opportunities. In natural systems, human intervention may facilitate adjustment to expected climate and its effects.

There are three further useful sub-definitions of adaptation:

- *Autonomous adaptation* - response to experienced climate and its effects, without planning explicitly or consciously focused on addressing climate change. Also referred to as spontaneous adaptation.
- *Incremental adaptation* - actions where the central aim is to maintain the essence and integrity of a system or process at a given scale.
- *Transformational adaptation* - adaptation that changes the fundamental attributes of a system in response to climate and its effects.

Ecosystem-based adaptation
The use of biodiversity and ecosystem services as part of an overall adaptation strategy to help people to adapt to the adverse effects of climate change. Ecosystem-based adaptation uses the range of opportunities for the sustainable management, conservation, and restoration of ecosystems to provide services that enable people to adapt to the impacts of climate change. It aims to maintain and increase the resilience and reduce the vulnerability of ecosystems and people in the face of the adverse effects of climate change.

Adaptive capacity
The ability of systems, institutions, humans, and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences.

Adaptive management
A process of iteratively planning, implementing, and modifying strategies for managing resources in the face of uncertainty and change. Adaptive management involves adjusting approaches in response to observations of their effect and changes in the system brought on by resulting feedback effects and other variables.

Exposure
The presence of people, livelihoods, species or ecosystems, environmental services and resources, infrastructure, or economic, social, or cultural assets in places that could be adversely affected.

Resilience
The capacity of a social-ecological system to cope with a hazardous event or disturbance, responding or reorganizing in ways that maintain its essential function, identity, and structure, while also maintaining the capacity for adaptation, learning, and transformation.

Sensitivity
The degree to which a system or species is affected, either adversely or beneficially, by climate variability or change. The effect may be direct (e.g., a change in crop yield in response to a change in the mean, range, or variability of temperature) or indirect (e.g., damages caused by an increase in the frequency of coastal flooding due to sea-level rise).

Vulnerability
The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts including sensitivity or susceptibility to harm and lack of capacity to cope and adapt.

Figure 1.8 - IPCC AR5 definitions of key terms used in this thesis (Agard *et al.* 2014)

1.6 Aims and Objectives

The overall aim of this thesis is to develop adaptation strategies to minimise climate change impacts on the conservation interests of Scotland's standing freshwaters. From the outset of the research process the intention has been to produce outputs with real practical applied significance. In particular, there were four principal objectives for this thesis:

- To increase our knowledge of the standing freshwater resource in Scotland. How many lakes are there, where are they and what are their characteristics?
- To assess the projected climate impacts to Scotland by the 2050s. How will temperature and precipitation change and what effect will these changes have on key hydrological and ecological components of the lake system?
- To explore the vulnerability of the lakes to change based on their sensitivity (a measure of system resilience and adaptive capacity) and the projected exposure to change.
- To move beyond broad adaptation principles to produce a set of adaptation strategies and actions which are both desirable and feasible to protect the conservation interest of Scotland's standing freshwaters over multiple spatial and temporal scales.

While this thesis is grounded in the Scottish standing freshwater resource it is informed by a much wider discourse surrounding the future management of our natural environment. **Chapter 1** has introduced the main themes and challenges this thesis aims to address, covering the background rationale of increasing pressures facing all our natural ecosystems in particular climate change impacts to ecohydrology. This introduces the thesis not simply as a work about Scottish lakes, but situates it in within a dialogue around how we can proactively minimise impacts to our environment through engaged and active conservation management at multiple spatial and temporal scales.

Chapter 2 explores the lake resource making use of the latest geospatial data and GIS techniques to investigate Scottish standing freshwaters in depth. This chapter attempts to answer key questions including investigating the number, distribution and density of Scotland's lakes and their hydromorphological characteristics. It also reviews the current conservation interest relating to Scotland's standing freshwaters including species and habitats of conservation priority and the current protected area system. Finally it links landscape scale approaches to conservation management.

Chapter 3 investigates the direct exposure to global climate change facing Scotland. Projected changes to global climate are shown to impact on the UK and Scotland using both the UKCP09 and HadGEM2-ES climate models. Mapping these climate projections allows clear visual interpretation of the data downscaled to Scotland. Incorporating the climate model data into a GIS we can further interrogate the results for specific locations. This chapter also provides a climate change spatial risk assessment highlighting those areas of Scotland projected to face the greatest changes to mean summer temperatures and precipitation. Many of the lakes within this area are already in challenging condition, and given that climate change impacts will likely exacerbate current pressures, management of these lakes will continue to be a major challenge.

Chapter 4 explores the vulnerability of Scotland's standing freshwaters. Vulnerability assessments have become increasingly popular in socio-ecological studies over the past decade as they allow the systematic combination of both empirical and expert based data sources to deal with complex systems. This chapter aimed to explore the concepts of vulnerability and sensitivity, and the closely related constructions of resilience and adaptive capacity. The vulnerability framework created for this study is based upon clear understandings of complex terminology and deliberately attempts to place resilience as a key part of the model, which has to date been missing from similar assessments.

To approach the issue of adaptation strategies themselves, **Chapter 5** used a multipart online survey with 40 participants actively involved in freshwater environmental management. Participants came from a wide array of organisations representing three broad stakeholder groups: researchers, practitioners and policy makers. For the first time a long list of over 80 adaptation actions specifically applicable to Scotland's standing freshwaters has been created. These actions, clustered into 12 adaptation strategies were analysed to explore both their desirability and feasibility, allowing environmental managers to focus and prioritise those adaptation options that are likely to have the greatest chance of success.

Finally, **Chapter 6** presents a general discussion of the issues raised throughout the thesis, and offers a series of policy-relevant recommendations for environmental managers working with the Scottish standing freshwater resource. While specifically targeted to the Scottish situation it is hoped that this discussion, centering around issues of scale, focus and priority in conservation management will have a wider resonance for those working with natural systems coming under increased pressure from climate, and other, pressures over the coming century.

Chapter 2 – Scotland's standing freshwaters: Placing 'lakes' in their landscapes

2.1 Introduction

To produce a comprehensive climate change adaptation strategy for conservation it is vital to have a clear understanding of what and where the resource is, and how this relates to current conservation measures (Dudgeon *et al.* 2006; Sutherland *et al.* 2010; Crossman *et al.* 2012). Until now the most comprehensive investigation of Scotland's outstanding standing freshwater resource was by Lyle and Smith (1994) much of which was based upon data collected by Smith and Lyle (1979) and the Murray and Pullar (1910) bathymetrical survey of over 560 lakes, known locally at lakes. Recent improvements in digital mapping and geographic information systems (GIS) mean we can now gain a much clearer understanding of the abundance, distribution, density and catchment relations of all UK standing freshwaters (Hughes *et al.* 2004). The recent proliferation of online resources also mean we have better access to data regarding species and habitats of conservation priority (see for example Scottish Natural Heritage's Sitelink and the National Biodiversity Network website), though comprehensive national scale surveys continue to be poorly funded and incomplete (Heino et al. 2009). Furthermore, there remains a great deal unknown about the links between physico-chemical, hydromorphological and ecological processes within lakes (Rowan *et al.* 2012).

Climate changes will impact the ecohydrology of standing freshwaters through multiple pathways, acting at different geographical scales and conditioned by sensitivities attributable to landscape setting (Dawson *et al.* 2003; Saloranta *et al.* 2009; George *et al.* 2010; Woodward *et al.* 2010; Dokulil 2013; Brucet *et al.* 2013). This is especially important in the face of other changing lake and catchment pressures – which include diffuse pollutants, morphological modification, recreation and invasive species – as climate change is likely to exacerbate these issues (Johnson *et al.* 2009; Wilby *et al.* 2010; Maltby *et al.* 2011; Moss 2014). Links between climate, hydrology and ecology are poorly understood and, while some attention has been paid to river systems, remarkably little study has taken place on standing freshwaters in the UK (Moss 2014). This is especially surprising in Scotland given that its lakes occupy approximately 3% of the country's land mass and contain more than 90% of the volume of Great Britain's total freshwater resource (Lyle & Smith 1994) – Loch Ness alone contains a greater volume of freshwater than is present in all the lakes of England and Wales combined. From the landscapes of the North West covered in small peat dominated pools, to high altitude mountain corrie lakes, to expansive open waters with shallow basins and large, deep valley lakes scoured from the landscape over multiple glaciations, they occupy a myriad of forms and sizes while contributing to habitats of international importance for numerous species (Nilsen *et al.* 2007; Etheridge *et al.* 2010; The Scottish Government 2013). Lakes are found in our most densely populated urban centres and throughout the wildest remote landscapes and there is pressing need across all geographic scales to conserve these environments in the face of changing water body, catchment and global pressures, including climate change in particular (Dudgeon *et al.* 2006; Maltby *et al.* 2011; Moss 2014).

The dominant mode of management for conservation globally is the designation of protected areas (Pimbert & Pretty 1995; Ervin & Congress 2003; Phillips *et al.* 2004; Alagador *et al.* 2014; Thomas & Gillingham 2015). These site designations provide the legislative power to an enforcing agency to modify, or curtail, the use and management of the area with the aim of preserving or enhancing the natural features therein (Cook *et al.* 2012). In Scotland, as elsewhere, the protected area system includes multiple designations that are based on national and international law. Indeed there are 24 different protected area designations in Scotland, many of which can apply to a single site (Barker & Stockdale 2008; Selman 2009). In the UK the main piece of legislation relating to nature conservation is the Wildlife and Countryside Act 1981. This Act is supplemented by the Nature Conservation (Scotland) Act 2004 in Scotland under which SNH designates Special Sites of Scientific Interest (SSSI). SSSIs are considered the most important protected area designation in Scotland, as they are the building block upon which other protected areas are founded (Gaston *et al.* 2006). It is an offence for any person to 'intentionally or recklessly' damage the designated features of an SSSI. SSSIs are managed by SNH, NGOs such as the RSPB or SWT and in some cases private land owners (Gaston *et al.* 2006).

The UK is also subject to EU environmental legislation in particular the Birds Directive (2009/147/EC) and the Habitats Directive (92/43/EEC). The Birds Directive (originally adopted in 1979 and updated and re-ratified in 2009) protects all wild birds, their nests, eggs and habitats within the European Community. It provides member states with the power and responsibility to classify Special Protection Areas (SPAs) to protect birds that are rare or vulnerable in Europe, as well as migratory birds and regular visitors. The Habitats Directive was adopted in 1992, complements and amends the Birds Directive. It is specifically designed to allow the European Community to meet its obligations under the Biodiversity Summit agreed at the Rio Earth Summit in 1992. The Habitats Directive allows the creation of Special Areas of Conservation (SACs) with a wider species and habitat mandate than SPAs. Collectively SPAs and SACs are known as Natura (2000) sites. The other notable protected area designation for freshwaters is the Ramsar Network. The Convention on Wetlands of International Importance (Ramsar) was adopted in the UK in 1976. All Ramsar sites in Scotland are also either SPAs or SACs, and many are also SSSIs. Although the boundaries of different designations are not always exactly the same there is significant overlap. Although there is no specific legal framework that safeguards Scottish Ramsar sites, they benefit from the measures required to protect and enhance the Natura and SSSI sites that they overlap. SNH also include Ramsar sites within its Site Condition Monitoring (SCM) programme. There are over 5000 sites across Scotland monitored through the SCM cycle including all those SSSIs, SPAs and SACs designated for standing freshwaters. The only alternative wide scale assessment of current ecological condition comes from those lakes that form part of the reporting structure for the EU Water Framework Directive (WFD; European Commission 2000). The implementation of the WFD has prompted renewed interest in standing freshwaters and ecological quality, but monitoring efforts and criteria remain focussed on only the largest of lakes and differ wildly across Europe (Rowan *et al.* 2006; Brucet *et al.* 2013; Poikane *et al.* 2014).

Standing freshwaters are an important part of both the physical and cultural landscape in Scotland, and their conservation interest does not simply lie in the diversity of species which inhabit their depths (Marsh & Anderson 2002; Schaich *et al.* 2010). Rather, the position of the standing water within the landscape and the hugely varied use both in/on/with the water, and in their catchments, must be recognised as important drivers in the search for a holistic conservation policy and climate change adaptation strategy (Lemieux & Scott 2011; Burch *et al.* 2014; Neff & Larson 2014). Species and habitats are not the only way of measuring the value of our natural environment and for many years landscape ecologists have investigated relationships between narratives of site specific species management and landscape scale conservation (Hansson & Angelstam 1991; Simberloff 1998). Recent advances in GIS have led to increasing number of studies looking in great detail at landscape characteristics and conservation (Turner 2005; Cumming 2011; Wiens 2012; Mazziotta *et al.* 2014) and, in particular, wild areas as a conservation priority (SNH 2008; Mc Morran *et al.* 2008; Moyes *et al.* 2011; Davis *et al.* 2013; Duputié *et al.* 2014). Studies using these techniques have been particularly important where wide scale data is lacking, as changes in land cover for example, monitored by remote sensing, can be used as a proxy for current condition of an area (Galbraith & Burns 2007; Bibby 2009; Weijters *et al.* 2009; Verburg *et al.* 2011).

This chapter aims to explore these issues making use of the latest geospatial data and GIS techniques to firstly investigate how many lakes there are in Scotland, their distribution, density and hydromorphological characteristics. Secondly, it will investigate the extent and focus of the current conservation interest predominantly focussed around protected areas designated for Scotland’s standing freshwaters. Finally, it will explore the links between lake, landscape and conservation in this system in particular the current condition of the resource and the intensity of catchment land cover.

2.2 Methods

2.2.1 Data sources and software packages

Data covering 25,569 standing freshwaters (>0.1ha) was extracted from the UK Lakes database (Hughes *et al.* 2004). Alternative sources, including digitised versions of Murray and Pullar's 1910 bathymetric survey, were used to clarify data where necessary. Unless otherwise specified below data was extracted from Microsoft Access databases and compiled in Microsoft Excel 2010. Statistical analysis was carried out in the R package v3.0.1 (R Core Team, 2013).

Spatial analysis and display was completed in ArcGIS 10 (ESRI, 2011) utilizing a range of standard package spatial analysis tools and the add-on Geospatial Modelling Environment programme Spatial Ecology (Beyer, 2011). Raw data and ESRI GIS shapefiles were also provided by the SEPA, SNH and the Climate X Change under licence. Further GIS data including country and regional border shapefiles and a digital elevation map (DEM) were sourced from Ordnance Survey DIGIMAP (digimap.edina.ac.uk) and the GoGeo database (gogeo.ac.uk). All geospatial data layers were converted to geographic projection GCS_OSGB_1936 using the British National Grid Projected Coordinate System with Transverse Mercator projection.

2.2.2 The standing freshwater resource

2.2.2.1 Abundance and distribution

Data extracted from the UK Lakes database included a Water Body Identification (WBID) number, name (where available), county and GB grid reference point for standing freshwaters in Scotland with surface area greater than 0.1 hectares (No.=25,569; See Figure 1). Whilst recognising the major conservation interests that lie in ponds and wetlands (Sayer *et al.* 2008; Rosset *et al.* 2013), this study focussed on those standing freshwaters with surface area greater than 2 hectares (defined as lakes in the National Ecosystem Assessment (Maltby *et al.* 2011)).

GB grid references were converted to latitude and longitude, which allowed the projection of point data in ArcGIS 10. This point data layer combined with the WBID became the base level upon which further data could be layered to produce a geodatabase and subsequently a comprehensive geographic information system (GIS) that could be interrogated to produce distribution and density maps. SEPA provided further polygon shapefiles for over 8000 lake and lake catchments that were subsequently incorporated into the GIS and joined to the point data.

2.2.2.2 Lake landscape density

Lake landscape density is calculated using kernel density function (Okabe *et al.* 2009) from the spatial analyst tool box in ArcGIS 10. This density tool distributes a measured quantity of an input point layer throughout a landscape to produce a continuous matrix layer highlighting those areas that are lake rich or lake poor. Density maps were produced for both number of lakes and lake surface area.

2.2.2.3 Hydromorphological character

For over 5000 lakes identified as greater than 2ha surface area, the UK Lakes database was further interrogated to provide data values for a series of categorical classifications relating to lake mean depth, alkalinity, size and altitude to be added to the GIS. This comprehensive data set for each lake was then extracted from the GIS to a *.csv file which allowed descriptive statistical analysis to be carried out in Excel. Lake and river catchment data were supplied as an ESRI shapefile by SEPA and analysed in ArcGIS 10. Catchment area and perimeter for each lake was calculated from the shapefile polygons. The ArcGIS addon software Spatial Ecology (Beyer 2011) was used to intersect point and polygon data to extract catchment altitude data from a digital elevation model (DEM). To investigate patterns and relationships within these data, two and four factor Burt table analyses (Greenacre and Blasius 2006) were calculated and a multivariate analysis was completed. Due to the categorical nature of the dataset a multiple correspondence analysis (MCA) was required (Crawley 2008). MCA was computed in R version 3.0.1 (R Core Team 2013) using the package FactoMineR (Le *et al*. 2008).

2.2.3 The conservation interest

2.2.3.1 Conservation status and protected areas

Details of those species of conservation priority in Scotland were sourced from a literature search and direct from SNH, the Scottish Biodiversity List and the Scottish Biodiversity

Strategy websites. ESRI GIS shapefiles were sourced from SNH for all protected area designations with a particular focus on those with specific freshwater designations: Sites of Special Scientific Interest (SSSI), Special Protected Area (SPA), Special Area for Conservation (SAC) and Ramsar convention protected areas. These data layers were processed and projected to GB National Grid and added to a data layer showing Scotland's outline. These layers were then intersected with the polygons depicting the location and extent of Scotland's standing freshwaters using the spatial join technique to form a new georeferenced data layer highlighting those standing freshwaters categorised directly as a SSSI or which were sited within the boundaries of another SSSI. Data regarding site condition for protected lakes was provided by SNH.

2.2.3.2 Landscape character and wildness

ESRI Shapefile data from two additional landscape classification maps recently produced by SNH were also added to the GIS. The Landscapes of Scotland map reflects the great diversity of landscapes within the country, and the regional distinctiveness that this creates. It is 'about place at the broad scale' and provides a national scale understanding of landscape characteristics. The Wild Lands map (Carver *et al.* 2012) was also incorporated into the GIS. This is a much more comprehensive analysis of Scotland's landscape character defining a wild area based on four principal attributes - the perceived naturalness of the land cover, the ruggedness of the terrain which is therefore challenging to cross, the remoteness from public roads, ferries or railway stations and finally the visible lack of buildings, roads, pylons and other modern artefacts. Data from the Land Cover Map 2007, Native Woodland Survey of Scotland, National Forestry Inventory and the Ordnance Survey were analysed at 25m resolution with each cell being assigned a 'naturalness score' from 1 (low perceived naturalness) to 5 (high perceived naturalness). The influence of surrounding area was also taken into account and the percentage breakdown for each of the 5 naturalness classes was calculated within 250m for each cell. These percentages were then multiplied by the cell naturalness score giving a range of scores from 100-500 which were then re-scaled from 1-256 to allow each layer to be analysed in combination. Each of these components was mapped (Carver *et al.* 2012) and a composite index of wild land quality was then derived by combining the individual attribute layers with equal weighting. This index is scaled from 1 (not wild) – 256 (very wild) and mapped across Scotland. From this analysis a list of 'core' wild areas is currently under consultation, which may be used to designate new or expanded protected areas. Wild areas are of increasing interest for conservation planners as it is very likely that wilder, more natural, areas will have greater adaptive capacity and resilience to environment changes (Mittermeier *et al.* 1998; Watson *et al.* 2009; Carver *et al.* 2012; Heller & Hobbs 2014). The mapped wild land composite layer data was used to create a lake wildness score by intersecting the wild land score raster with lake point data using the 'Multi Values to Points' tool from the ArcGIS 10 Extraction Toolbox.

2.2.4 Current condition

Data relating to the current condition of Scotland's standing freshwaters are limited both in spatial and temporal extent. For those lakes designated as SSSIs Site Condition Monitoring data was provided by SNH for the most recent round of surveys (2009/10). For those lakes monitored under the WFD, condition data are freely available from SEPA with an interactive tool and data access online.

A further proxy for condition or habitat quality can be the intensity of land cover use within a lake catchment (Galbraith & Burns 2007; Cheruvelil & Soranno 2008; Dessel *et al.* 2008; Weijters *et al.* 2009). Those lakes in high intensity urban or agricultural landscapes are likely to be poorer quality with less adaptive capacity than those in more natural or less impacted areas (Owen *et al.* 2012; Watts *et al.* 2015). Data from the LCM2007 dataset (CEH 2011; Morton *et al.* 2011), provided by Climate X Change under licence from CEH/NERC, was imported into the GIS covering the full extent of the country. This data set was then intersected with the lake catchment shapefiles provided by SEPA (see Figure 2.1 for an example). For each lake catchment the percentage of each land cover type (see Table 2.1) was calculated using the Tabulate Intersection tool in ArcGIS 10.1 (ESRI 2011). Subsequently a simple land cover intensity matrix (Table 2.2) was created to categorise each catchment as High, Medium or Low intensity (Strayer *et al.* 2003; Dessel *et al.* 2008; Kleijn *et al.* 2009).

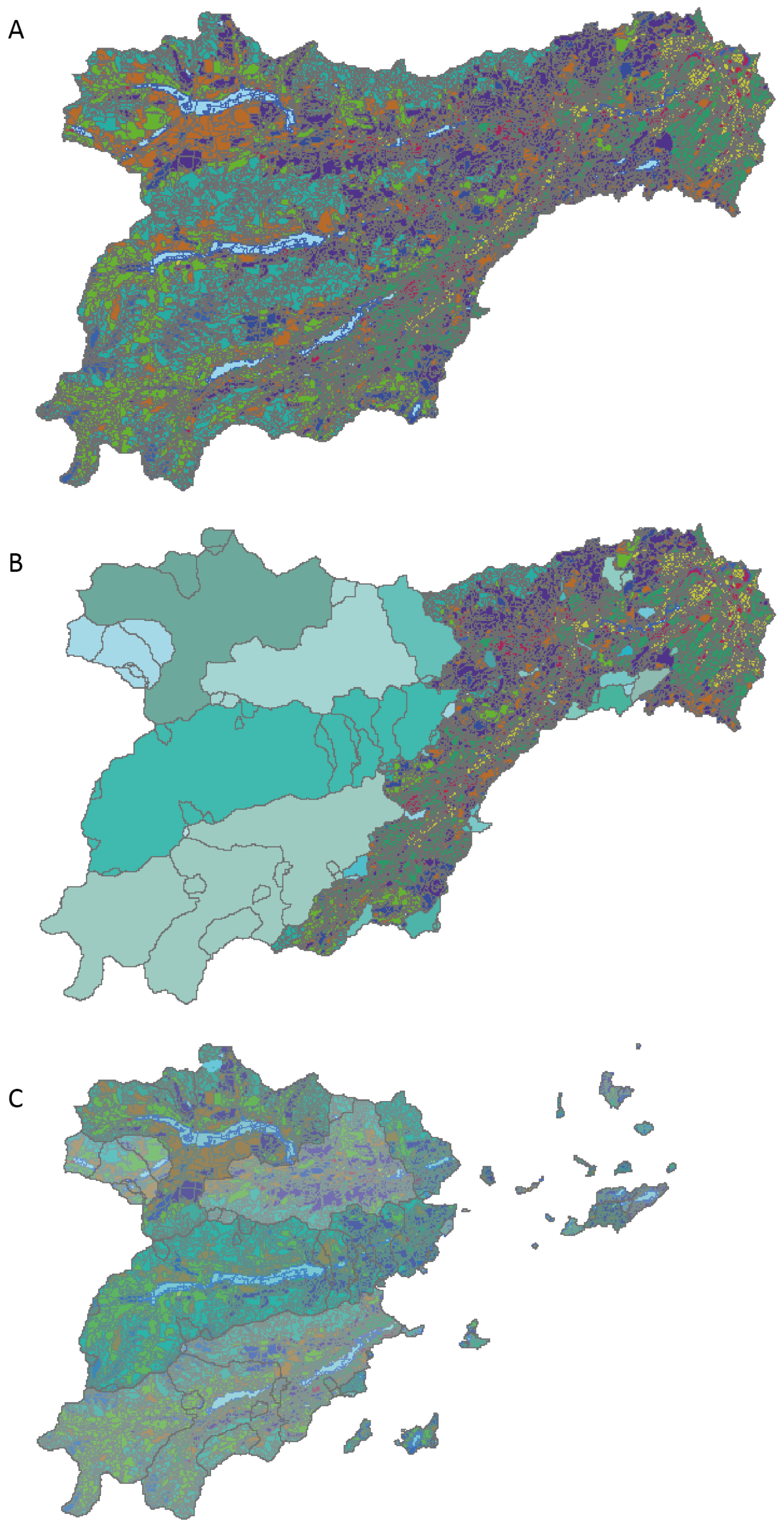


Figure 2.1 - An example of data preparation for lake catchment land cover mapping for the River Beauly catchment in Northern Scotland. A) illustrates the first step, importing the LCM2007 data, clipping it to Scotland and integrating with the GIS to allow investigation at multiple scales. B) illustrates the lake catchments within this particular river catchment and C) illustrates the intersection of these data sets. For each lake catchment the percentages of each land cover type were then calculated.

Table 2.1 – LCM 2007 Land Cover classifications (CEH 2011). * indicates high intensity land cover class (Hendrickx *et al.* 2007; Kleijn *et al.* 2009; Tuck *et al.* 2014)

LCM2007 class	**LCM2007 class number**
Broadleaved Woodland	1
Coniferous Woodland	2*
Arable and Horticulture	3*
Improved Grassland	4*
Rough Grassland	5
Neutral Grassland	6
Calcareous Grassland	7
Acid Grassland	8
Fen, Marsh and Swamp	9
Heather	10
Heather Grassland	11
Bog	12
Montane Habitats	13
Inland Rock	14
Saltwater	15
Freshwater	16
Supra-littoral Rock	17
Supra-littoral Sediment	18
Littoral Rock	19
Littoral Sediment	20
Saltmarsh	21
Suburban	22*
Urban	23*

Table 2.2 – Calculated catchment land cover intensity. If >50% of lake catchment land cover is from classes 2,3,4,22,23 (see Table 2.1) the lake catchment is scored as High intensity. If >=15% - Medium intensity and <15% - Low intensity (Galbraith & Burns 2007; Noyes *et al.* 2009).

Catchment Land Cover Intensity	
HIGH	>50% CATCHMENT
MID	>=15% CATCHMENT
LOW	<15% CATCHMENT

2.3 Results

2.3.1 The standing freshwater resource

2.3.1.1 Abundance and distribution

The number of standing freshwaters with surface area >0.1ha (approximately what would be mapped on a 1:20,000 scale OS map) in Scotland is 25,569 (mapped in Figure 2.3 and outlined in Figure 2.2, below). Of these, 20,424 are considered ponds and 5,165 lakes (above 2ha surface area; Maltby *et al.* 2011). Box and quartile plots are a convenient way of graphically depicting descriptive statistics to illustrate groups of numerical data through their range (Crawley 2008). What is evident in Figure 2.2 is that this is not a normally distributed data set but rather is highly skewed with the vast majority being very small with only a very few large outliers. This is especially evident in the boxplot, where the mean and interquartile ranges are indistinguishable from each other due to the outliers that show the small number of very large lakes. Figure 2.4 maps the distribution of lakes by surface area throughout Scotland. The map highlights the high number of small lakes in the North West Highlands and Islands, and the relative lack of water bodies in the South and East of the country. Table 2.4 highlights the distribution of lakes through local authority political regional boundaries.

Surface area (ha)	n
0.1-1	12494
1-2	7908
2-10	3624
10-50	1205
50-500	296
500-3000	38
3000-7000	4

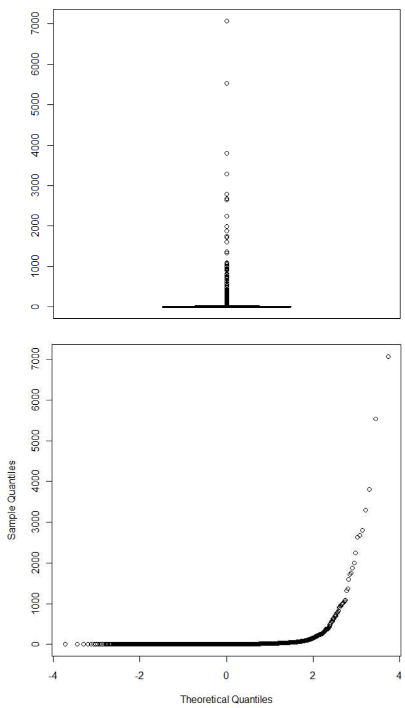


Figure 2.2 – The total number (No.=25,569) of standing freshwaters in Scotland categorised by surface area (ha). Box plot (top) and quartile plot (bottom) illustrating the statistical distribution of lakes by surface area.

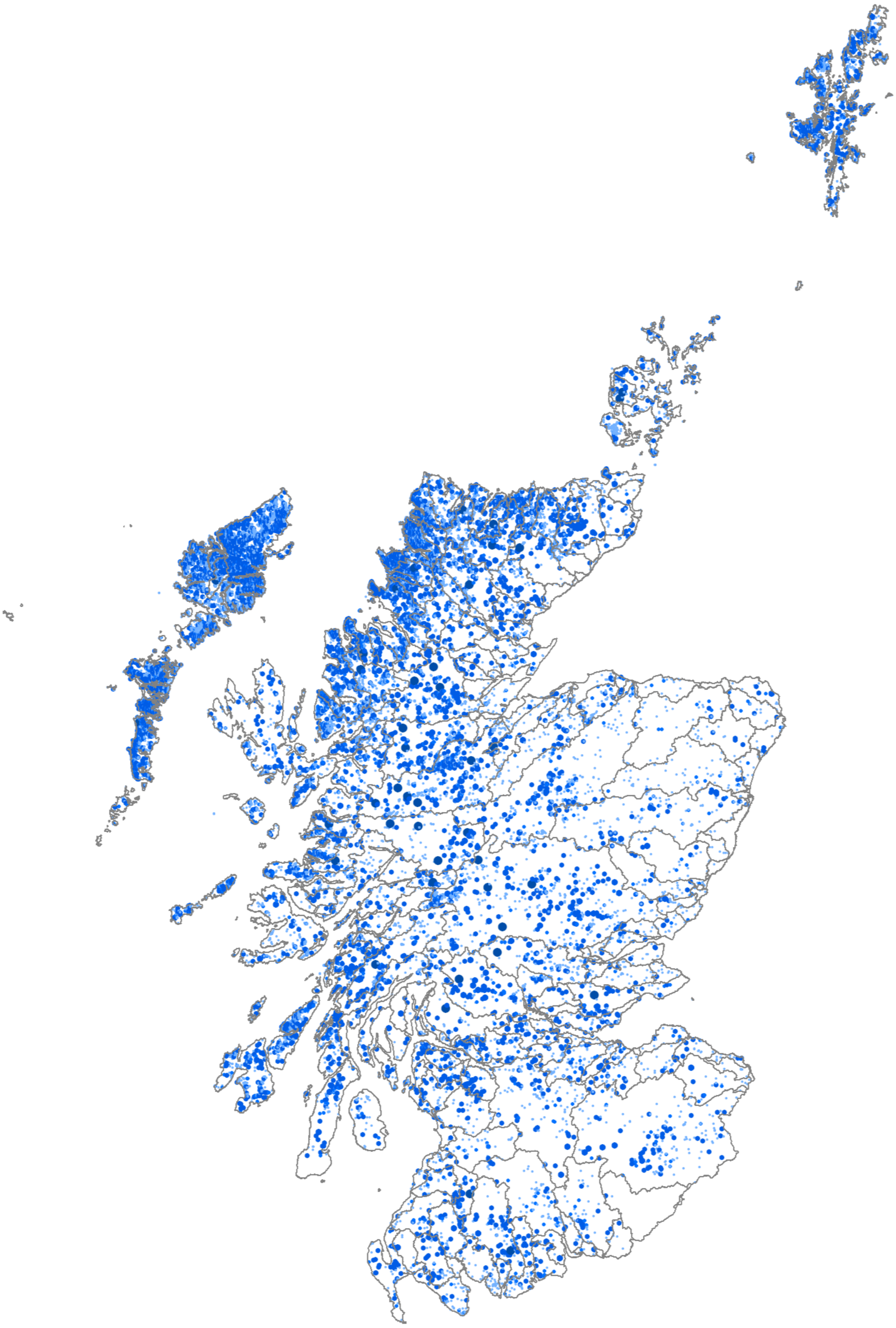


Figure 2.3 – All standing freshwaters greater than 0.1 ha surface area plotted across Scotland (No.=25,569).
The grey lines indicate Scotland's main river catchments.

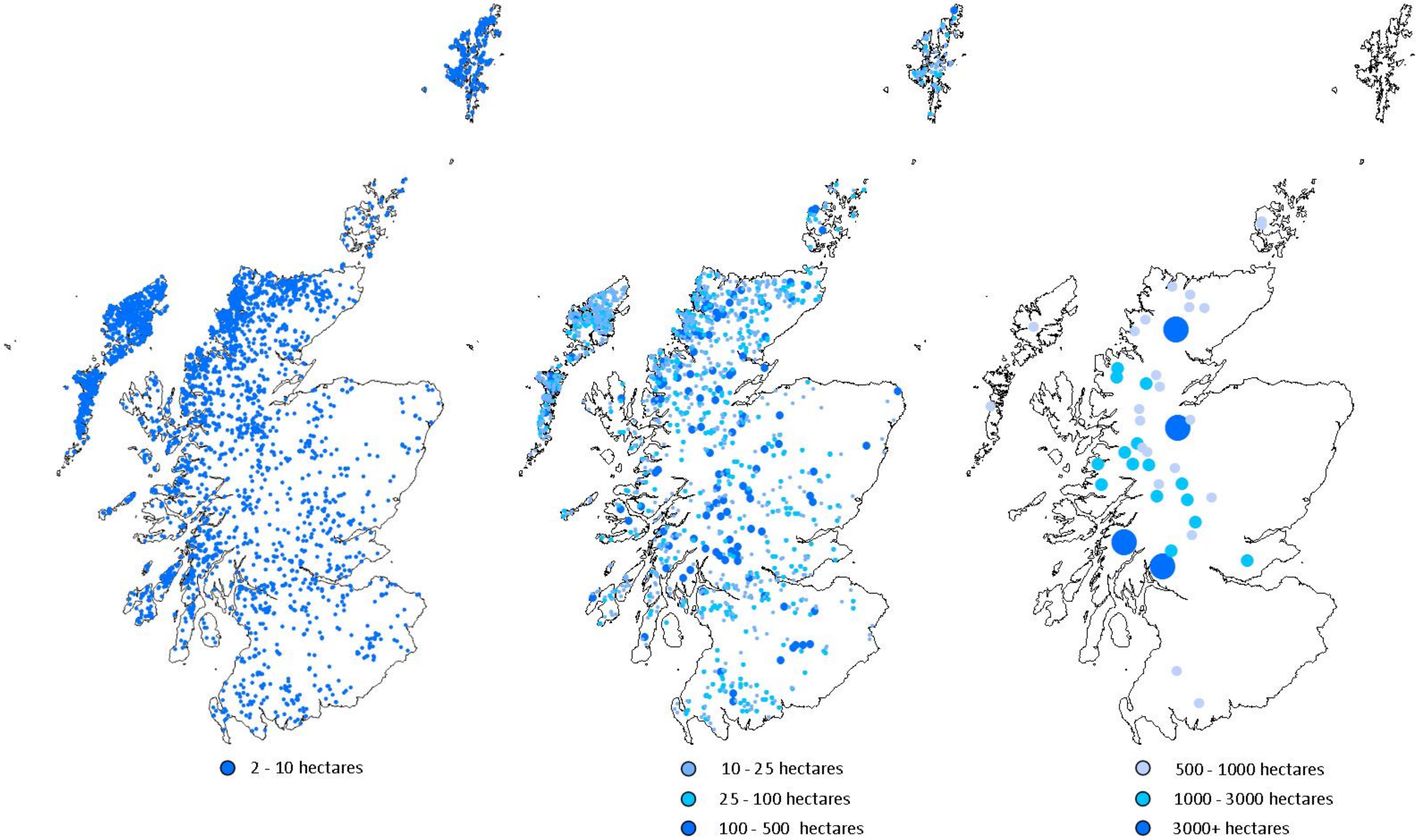


Figure 2.4 – The distribution of Scotland's lakes displayed by surface area

Table 2.3 - Number of lakes per region showing total surface area and percentage of total resource. The majority (41.07% by number, 50.71% by surface area) occur within the Highlands.

REGION	NUMBER	SURFACE AREA (HA)	% TOTAL NUMBER	% TOTAL AREA
Aberdeenshire	46	942	0.89	0.66
Angus	29	813	0.56	0.57
Argyll and Bute	458	18,282	8.86	12.78
City of Aberdeen	4	31	0.08	0.02
City of Dundee	2	15	0.04	0.01
City of Edinburgh	11	120	0.21	0.08
City of Glasgow	3	46	0.06	0.03
Clackmannanshire	1	56	0.02	0.04
Dumfries and Galloway	156	3,766	3.02	2.63
East Ayrshire	24	1,243	0.46	0.87
East Dunbartonshire	11	110	0.21	0.08
East Lothian	13	132	0.25	0.09
East Renfrewshire	23	455	0.45	0.32
Falkirk	20	189	0.39	0.13
Fife	45	830	0.87	0.58
Highland	2122	72,513	41.07	50.71
Inverclyde	17	360	0.33	0.25
Midlothian	7	227	0.14	0.16
Moray	26	266	0.50	0.19
Na h-Eileanan an Iar	1312	16,422	25.39	11.48
North Ayrshire	29	366	0.56	0.26
North Lanarkshire	23	486	0.45	0.34
Orkney Islands	62	3,252	1.20	2.27
Perth and Kinross	149	10,480	2.88	7.33
Renfrewshire	17	379	0.33	0.27
Scottish Borders	55	1,221	1.06	0.85
Shetland Islands	341	3,173	6.60	2.22
South Ayrshire	34	620	0.66	0.43
South Lanarkshire	25	454	0.48	0.32
Stirling	77	5,243	1.49	3.67
West Dunbartonshire	15	186	0.29	0.13
West Lothian	10	320	0.19	0.22

2.3.1.2 Lake landscape density

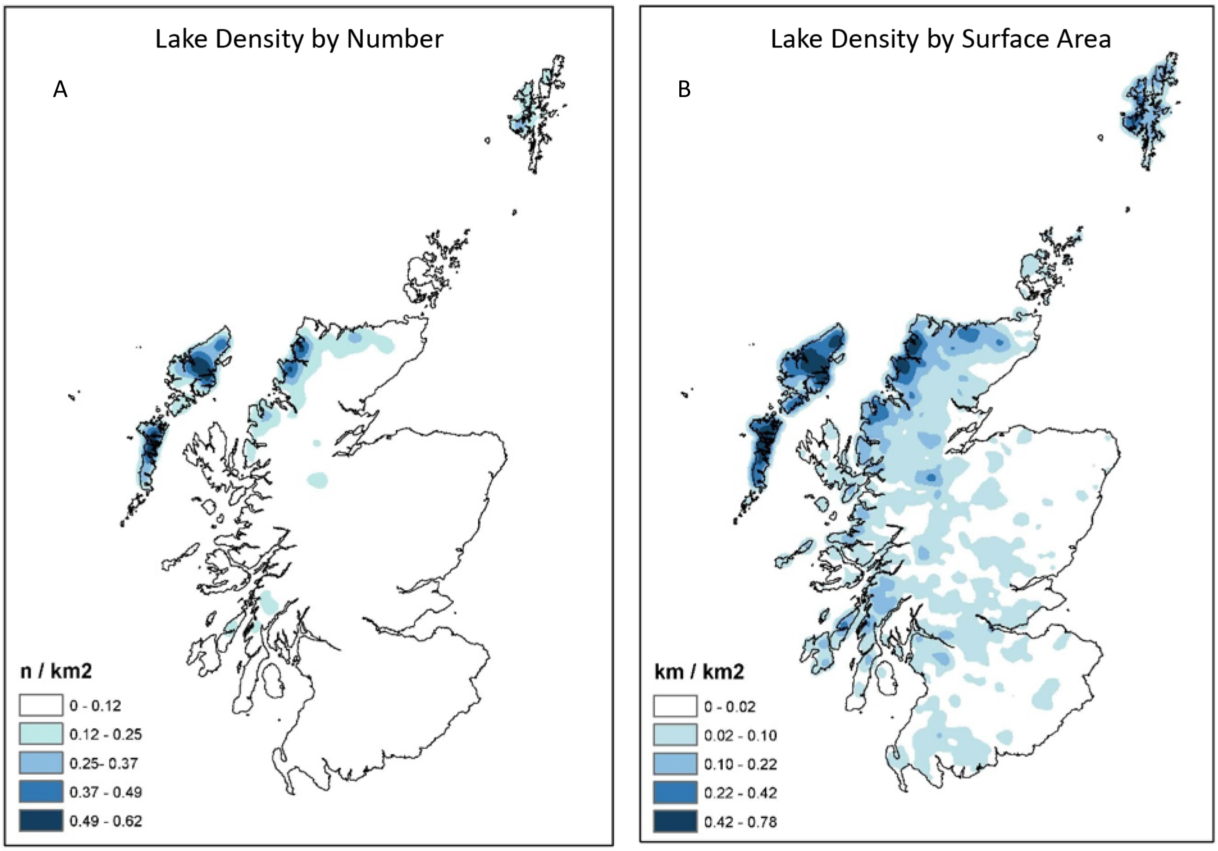


Figure 2.5 - Density of lake distribution across Scotland by A) number of lakes and B) surface area (km^2)

As illustrated by Figures 2.2 to 2.4, the distribution of lakes is uneven across Scotland. To further investigate this relationship of water with Scotland's landscapes, the density of lakes is mapped for both number of water bodies (A) and surface area per km^2 (B). Figure 2.5 (A) highlights the extreme density of number of very small water bodies in the North and West of the country. Figure 2.5 (B) illustrates a more balanced density map which highlights the surface area of water per km^2. Again this highlights the importance of the North and West of the country for their standing water resources, acknowledging the fact that the majority of these are extremely small. The map also highlights those areas of Scotland that are relatively lake poor. Conversely this may mean that lakes in these areas have a greater local significance and importance in terms of the use value and potentially the conservation interest.

2.3.1.3 Hydromorphological character

As shown in Table 2.4, the majority of Scotland's lakes are very small, shallow, low altitude and low alkalinity. These categorisations are based on the way the lake was formed, and strongly influence the biotic character of the site (Webster *et al.* 2000; Rowan *et al.* 2004; Duigan *et al.* 2007) . Understanding whether there are natural groupings across the country could allow targeted management strategies to be identified. A further more detailed analysis of these categorisations is provided in the Burt (two factor) analysis shown in Table 2.5 and in the full four-way Factor Analysis, Table 2.6 (cf. Greenacre and Blasius 2006). These analyses begin to explore patterns that appear within the data set and highlight those common and rare hydromorphological types. For example, to evaluate how many Large (>50 ha surface area) lakes there are in Scotland the answer – 335 – can be quickly extrapolated from Table 2.4. To assess how many Large lakes are also Very Shallow (<3m mean depth) Table 2.5 can be examined to provide the answer – 49. For more complex relationships Table 2.6 can be inspected – for example we now know there are only 6 Large, Low Alkalinity, Very Shallow, Low Altitude lakes in Scotland. To examine which 6 lakes they are, or where they are found the GIS can be interrogated to provide this information.

Table 2.4 - The number of Scottish lakes with certain hydromorphological characteristics, assessed by Alkalinity, Mean Depth, Altitude and Size (data from UK Lakes Database).

Alkalinity (ALK)		Mean Depth (DEPTH)		Altitude (ALT)		Size	
Brackish	36	Deep (>15m; D)	64	High (>400m; H)	335	Large (>50ha; L)	335
Marl	54	Shallow (3-15m; Sh)	4878	Mid (200-400m; M)	1152	Small (10-50ha; S)	1189
Peat (P)	737	Very Shallow (<3m; VSh)	225	Low (<200m; L)	3660	Very Small (2-10ha; VS)	3643
Low (LA)	2407						
Mid (MA)	1278						
High (HA)	655						

To investigate these relationships further, to look for patterns or groupings within these categories, requires the use of a Multiple Correspondence Analysis (MCA), the results of which are shown in Figure 2.5. The analysis shows no clear clustering of lakes around these categorical variables (Dim 1: 12.2%; Dim 2: 13.22%), indicating that these factors alone are not sufficient to create a hydromorphological typology of lakes.

Table 2.5 – Burt table (two factor analysis) of lake hydromorphological characteristics. See Table 2.4 for abbreviations.

		ALK						ALT			DEPTH			SIZE		
		Brackish	Marl	Peat	LA	MA	HA	L	M	H	VSh	Sh	D	VS	S	L
ALK	Brackish	36						36	-	-	3	33	-	25	9	2
	Marl		54					45	9	-	2	52	-	38	15	1
	Peat			737				663	56	18	19	718	-	565	165	7
	LA				2407			1356	750	301	83	2285	39	1751	506	150
	MA					1278		998	247	33	60	1194	24	831	316	131
	HA						655	562	90	3	58	596	1	433	178	44
ALT	L	36	45	663	1356	998	562	3660			175	3443	42	2571	855	234
	M	-	9	56	750	247	90		1152		39	1094	19	807	256	89
	H	-	-	18	301	33	3			355	11	341	3	265	78	12
DEPTH	VSh	3	2	19	83	60	58	175	39	11	225			87	89	49
	Sh	33	52	718	2285	1194	596	3443	1094	341		4878		3555	1095	228
	D	-	-	-	39	24	1	42	19	3			64	1	5	58
SIZE	VS	25	38	565	1751	831	433	2571	807	234	87	3555	1	3643		
	S	9	15	165	506	316	178	855	256	89	89	1095	5		1189	
	L	2	1	7	150	131	44	234	78	12	49	228	58			335

Table 2.6 – Burt Table (four factor analysis) of lake hydromorphological characteristics. See Table 2.4 for abbreviations.

ALK	DEPTH	ALT	SIZE		
			L	S	VS
P	D	High	0	0	0
		Mid	0	0	0
		Low	0	0	0
	Sh	High	0	3	14
		Mid	0	10	46
		Low	6	143	496
	VSh	High	0	0	1
		Mid	0	0	0
		Low	1	9	8
Marl	D	High	0	0	0
		Mid	0	0	0
		Low	0	0	0
	Sh	High	0	0	0
		Mid	1	1	6
		Low	0	12	32
	VSh	High	0	0	0
		Mid	0	1	0
		Low	0	1	0
Brackish	D	High	0	0	0
		Mid	0	0	0
		Low	0	0	0
	Sh	High	0	0	0
		Mid	0	0	0
		Low	2	7	24
	VSh	High	0	0	0
		Mid	0	0	0
		Low	0	2	1
LA	D	High	1	2	0
		Mid	13	1	0
		Low	21	1	0
	Sh	High	7	57	225
		Mid	40	155	513
		Low	58	258	972
	VSh	High	0	1	8
		Mid	4	9	15
		Low	6	22	18
MA	D	High	0	0	0
		Mid	4	0	1
		Low	18	1	0
	Sh	High	4	13	15
		Mid	20	56	159
		Low	67	220	640
	VSh	High	0	1	0
		Mid	3	1	3
		Low	15	24	13
HA	D	High	0	0	0
		Mid	0	0	0
		Low	1	0	0
	Sh	High	0	1	2
		Mid	4	21	62
		Low	19	138	349
	VSh	High	0	0	0
		Mid	0	1	2
		Low	20	17	18

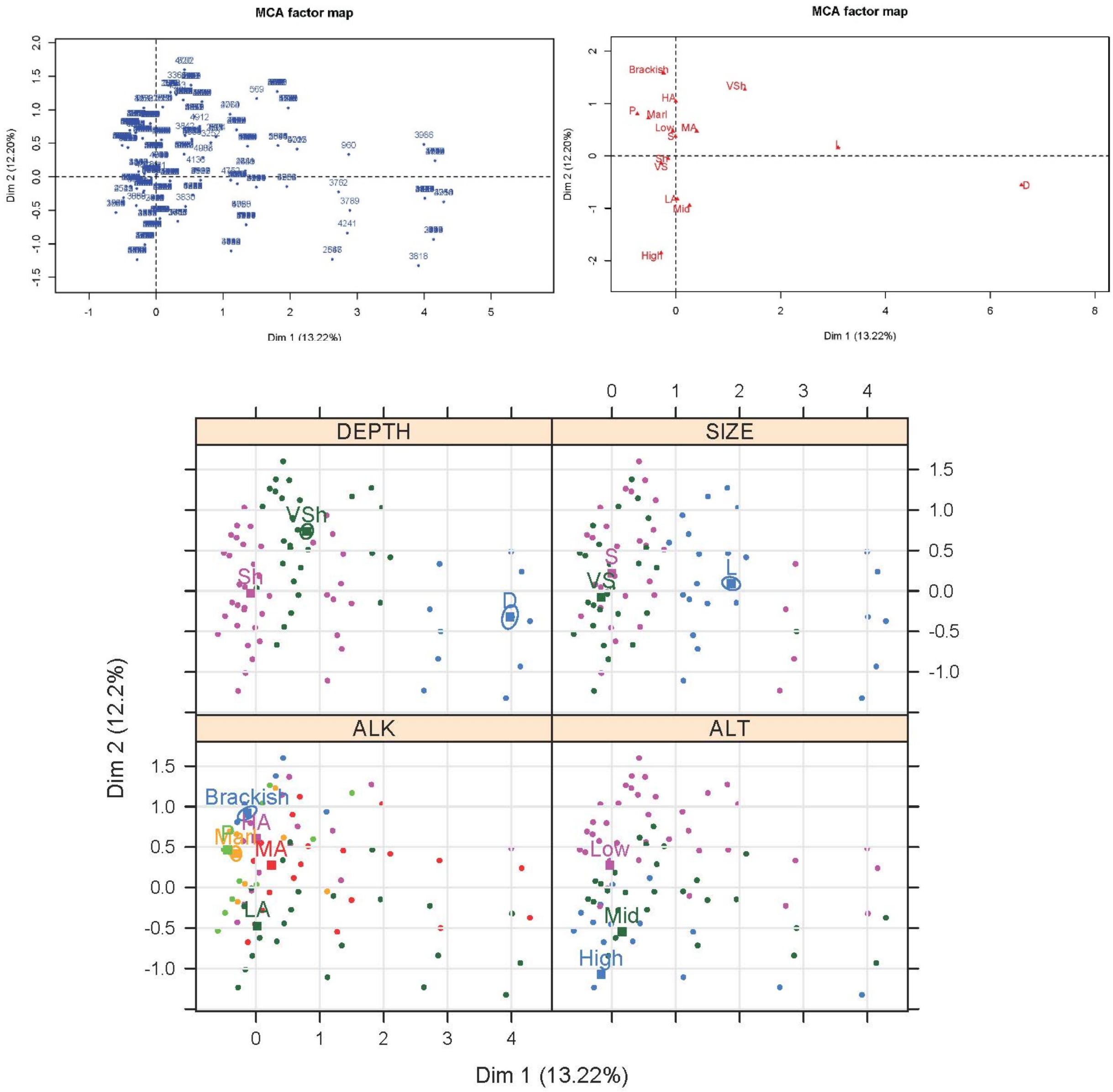


Figure 2.5 – Multiple correspondence analyses of hydromorphological characteristics of Scotland's lakes.

2.3.3 The conservation interest

2.3.3.1 Conservation status and protected areas

The Scottish Biodiversity List highlights 40 habitats and 1,947 species across the full extent of the country and all taxonomic groups, which are of conservation priority in Scotland. At the broad habitat level, standing freshwaters are highlighted as priority (Table 2.7). Of these broad habitat designations both Eutrophic and Mesotrophic standing waters are highlighted as 'Conservation Action Needed', while Oligotrophic and Dystrophic standing waters are highlighted to 'Avoid negative impacts'. As well as these habitat level priorities across the standing freshwater resource base there are a number species associated with standing freshwaters which have been highlighted as having particular conservation importance, outlined in Table 2.8.

Table 2.7 - Scottish Biodiversity List - Freshwater & Wetland Habitats of conservation priority. Lake systems are highlighted in grey.

Ecosystem Grouping	Habitat	Conservation action needed	Avoid negative impacts	Watching brief only	RE	SD	H1	H2	H3	H4
Freshwater & Wetland	Coastal and floodplain grazing marsh			Yes	***		Yes			
Freshwater & Wetland	Eutrophic standing waters	Yes	Yes		****	Yes	Yes		Yes	
Freshwater & Wetland	Lowland fens	Yes			***	Yes	Yes		Yes	
Freshwater & Wetland	Lowland raised bog	Yes	Yes		****	Yes	Yes			
Freshwater & Wetland	Mesotrophic lakes	Yes	Yes		***	Yes	Yes		Yes	
Freshwater & Wetland	Oligotrophic and dystrophic lakes		Yes		***		Yes			
Freshwater & Wetland	Ponds	Yes			***	Yes	Yes		Yes	
Freshwater & Wetland	Reedbeds			Yes	**		Yes			
Freshwater & Wetland	Rivers	Yes			****	Yes	Yes		Yes	

Key

SD – Significant Decline	RE – Relative Extent	Scottish Priority
> 25% of habitat assessed as declining (2008 UK BAP report) or in unfavourable condition (Site Condition Monitoring)	Order of magnitude (in hectares): * 10 ** 100 ***1000 **** 10000	H1 - on UK BAP list H2 - Rare in Scotland (<10 sites) H3 - Important for supporting species H4 - Habitat unique to Scotland (within UK)

Table 2.8 – Scottish Biodiversity List Species of conservation priority associated with standing freshwater habitats

Main group	**Taxon group**	**Scientific Name**	**Common name**	**Conservation action needed**	**Avoid negative impacts**	**Watching brief only**	**TS**	**LPS**	**S1**	**S2**	S3	**S4**	**S5**	**S6**
Mammals	land mammal	*Lutra lutra*	Otter		Yes		NT	EPS [1,2,3]	Yes	Yes				
Mammals	land mammal	*Arvicola amphibius*	Water Vole	Yes	Yes			WCA 1981	Yes				Yes	
Reptiles & amphibians	amphibian	*Bufo bufo*	Common Toad		Yes			WCA 1981	Yes					
Reptiles & amphibians	amphibian	*Triturus cristatus*	Great Crested Newt		Yes			EPS [1,2,3]	Yes	Yes				
Fish	bony fish	*Acipenser sturio*	Sturgeon	Yes	Yes		CR	EPS [1,2,3]		Yes	Yes	Yes		
Fish	bony fish	*Alosa alosa*	Allis Shad	Yes	Yes			HR 1994 [2,3]	Yes	Yes	Yes	Yes		
Fish	bony fish	*Alosa fallax*	Twaite Shad	Yes	Yes			HR 1994 [2,3]	Yes	Yes	Yes	Yes		
Fish	bony fish	*Anguilla anguilla*	Eel			Yes	CR		Yes					
Fish	bony fish	*Coregonus albula*	Vendace	Yes	Yes		EN	HR 1994 [2,3]	Yes		Yes	Yes	Yes	
Fish	bony fish	*Coregonus lavaretus*	Powan	Yes	Yes			HR 1994 [2,3]			Yes	Yes		
Fish	bony fish	*Osmerus eperlanus*	Smelt	Yes								Yes	Yes	
Fish	bony fish	*Salmo salar*	Atlantic Salmon	Yes	Yes			HR 1994 [3]		Yes				
Fish	bony fish	*Salmo trutta*	Brown Trout	Yes					Yes				Yes	
Fish	bony fish	*Salvelinus alpinus*	Arctic Charr			Yes			Yes					
Fish	jawless fish	*Lampetra fluviatilis*	River Lamprey		Yes			HR 1994 [3]		Yes				
Fish	jawless fish	*Lampetra planeri*	Brook Lamprey		Yes			ELD		Yes				
Birds	bird	*Gavia arctica*	Black-throated Diver		Yes		Amber	ELD		Yes				
Birds	bird	*Gavia stellata*	Red-throated Diver		Yes		Amber	ELD		Yes				
Birds	bird	*Melanitta nigra*	Common Scoter	Yes	Yes		Red	WCA 1981 [3]	Yes				Yes	
Birds	bird	*Pandion haliaetus*	Osprey		Yes		Amber	WCA 1981 [3]		Yes				

Birds	bird	*Podiceps auritus*	Slavonian Grebe	Yes	Yes		Amber	WCA 1981 [3]		Yes			Yes
Birds	bird	*Podiceps grisegena*	Red-necked Grebe	Yes	Yes		Amber	ELD			Yes	Yes	
Birds	bird	*Podiceps nigricollis*	Black-necked Grebe	Yes	Yes		Amber	WCA 1981 [3]			Yes	Yes	
Birds	bird	*Cygnus columbianus*	Bewick's Swan		Yes		Amber	WCA 1981 [3]		Yes			
Birds	bird	*Cygnus cygnus*	Whooper Swan	Yes	Yes		Amber	WCA 1981 [3]		Yes	Yes	Yes	
Birds	bird	*Anser fabalis*	Bean Goose	Yes	Yes		Amber	ELD				Yes	
Birds	bird	*Branta leucopsis*	Barnacle Goose		Yes		Amber	ELD		Yes			
Birds	bird	*Anser albifrons*	Greenland White-fronted Goose	Yes	Yes			ELD		Yes			
Non vascular plants	stonewort	*Nitella gracilis*	Slender Stonewort	Yes	Yes		VU		Yes		Yes	Yes	
Vascular plants	flowering plant	*Najas flexilis*	Slender Naiad		Yes			EPS [1,2,3]	Yes	Yes			
Vascular plants	flowering plant	*Potamogeton rutilus*	Shetland Pondweed	Yes					Yes		Yes		
Vascular plants	flowering plant	*Rumex aquaticus*	Scottish Dock	Yes	Yes		VU				Yes	Yes	

Key

TS - Threatened Species (IUCN Red List Categories)	**LPS - Legally Protected Species**	**Scottish Priority**
CR - Critically Endangered	EPS - European Protected Species	S1 - on UK BAP list
EN - Endangered	1 HR 1994 - Habitat Regulations 1994	S2 - International Obligation
VU - Vulnerable	2 WCA 1981 - Wildlife and Countryside Act 1981	S3 - Rare in the UK (<16 sites)
NT- Near Threatened	3 ELD - Environmental Liability Directive	S4 - Rare in Scotland (<6 sites)
DD - Data Deficient		S5 - Species in Decline (over 25 years or other appropriate time period)
EX - Extinct		S6 - Endemic to Scotland

2.3.3.2 Current protected area network

The number of all SSSI, SAC, SPA and RAMSAR protected areas are shown in Table 2.9 and their full extent mapped in Figure 2.7. SSSIs are the basis of the other designations and all RAMSAR sites are also SPAs, so there is considerable overlap in designation. Of Scotland's 1,426 SSSIs 145 are designated specifically for standing freshwater protection based on their trophic status - a continuum based on measured total phosphorus levels within the water body. The number of each designation is shown in Table 2.10 and mapped in Figure 2.8.

Table 2.9 – Number of freshwater protected areas in Scotland

Protected Area Designation	**Total No.**	**No. Freshwater**
Special Site of Scientific Interest (SSSI)	1426	145
Special Area of Conservation (SAC)	252	61
Ramsar	51	11

Table 2.10 – Number of freshwater protected areas organised by feature designation

SSSI (No.=145)	
DESIGNATED FEATURES	**No.**
Eutrophic loch	34
Mesotrophic loch	38
Dystrophic and oligotrophic lakes	8
Oligotrophic loch	34
Base-rich loch	11
Loch trophic range	4
Dystrophic loch	4
Oligo-mesotrophic loch	5
Machair loch	6
Meso-eutrophic loch	1

SAC (No.=61)	
DESIGNATED FEATURES	**No.**
Acid peat-stained lakes and ponds	16
Clear-water lakes or lakes with aquatic vegetation and poor to moderate nutrient levels	32
Nutrient-poor shallow waters with aquatic vegetation on sandy plains	1
Calcium-rich nutrient-poor lakes, lakes and pools	4
Naturally nutrient-rich lakes or lakes which are often dominated by pondweed	8

RAMSAR / SPA (No.=11)	
DESIGNATED FEATURES	**No.**
Oligotrophic loch	4
Eutrophic loch	4
Mesotrophic loch	1
Machair loch	1
Loch trophic range	1

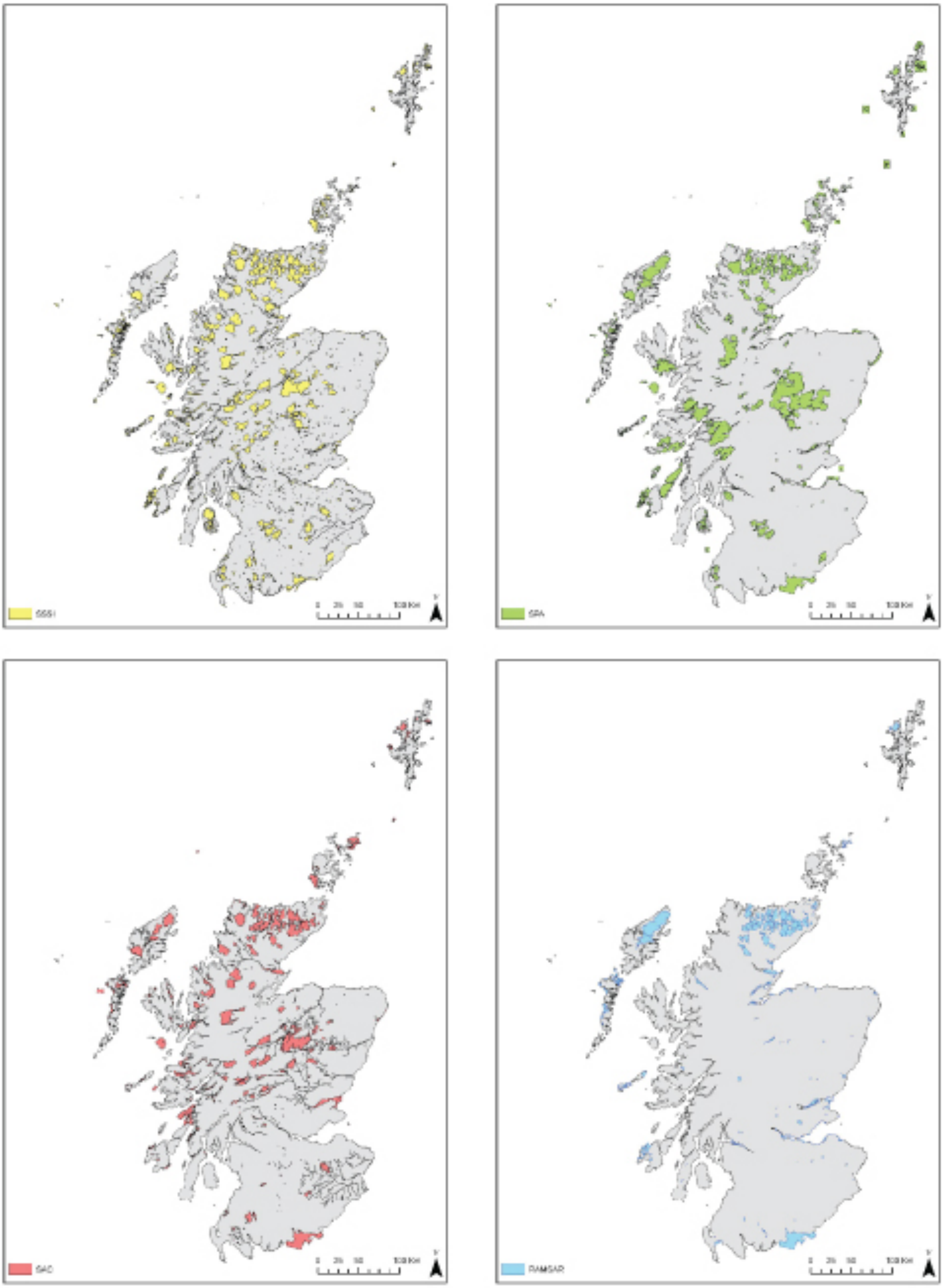


Figure 2.6 – Extent of all SSSI (yellow), SPA (green), SAC (red) and Ramsar (blue) sites in Scotland.

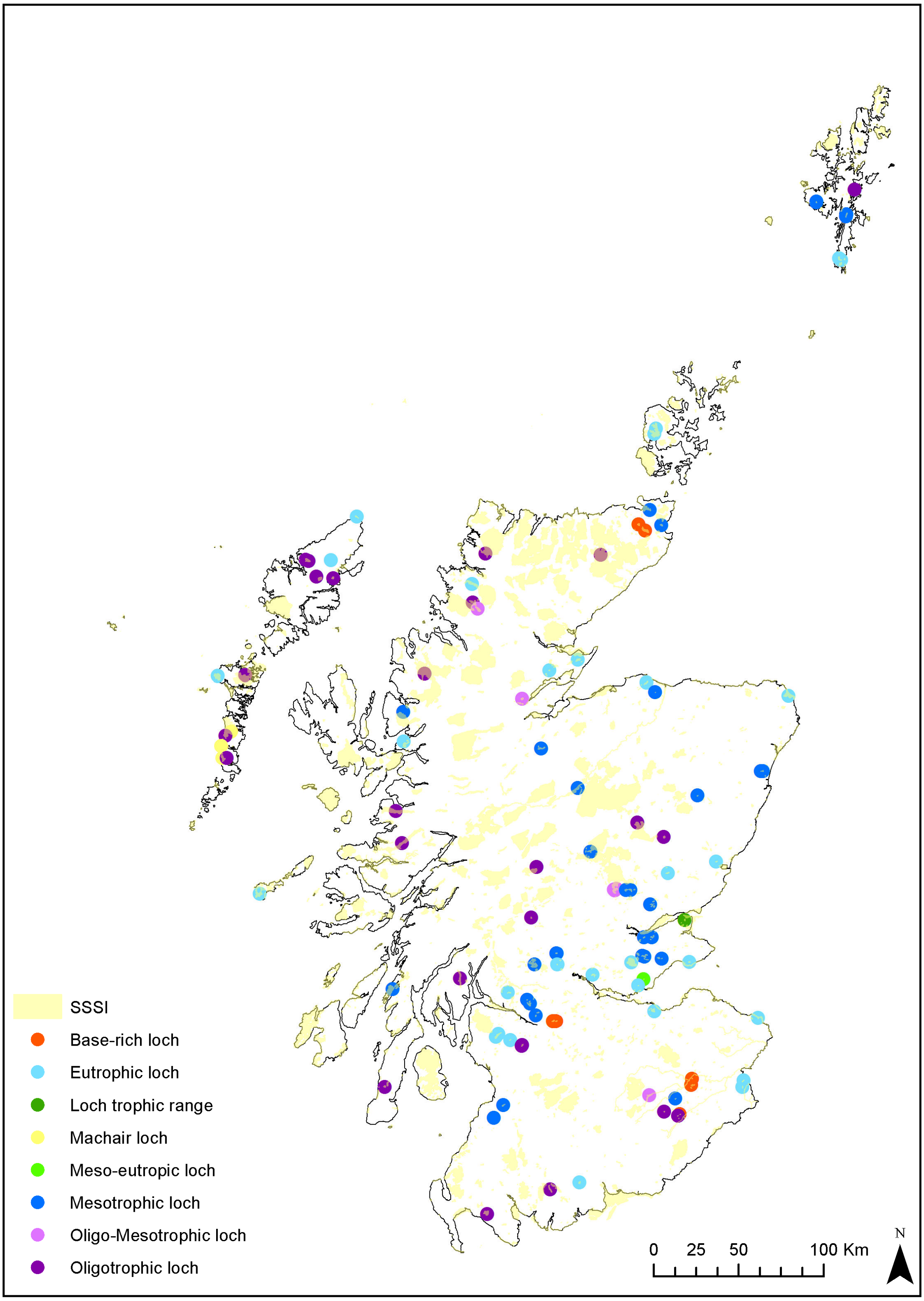


Figure 2.7 – Map of Scotland illustrating the location of all designated standing freshwater SSSIs

2.3.3.2 Wildness

Figure 2.9 illustrates the Scottish Wild Lands Map (composite score; SNH) with lake wildness score points overlaid. Table 2.11 indicates Scotland's 10 'wildest' lakes and their wildness scores (max 256). Those lakes in the wildest areas are most likely the most 'natural', with their hydromorphological characteristics under the least amount of pressure and therefore likely to have greatest resilience to change (Dudgeon *et al.* 2006; Naidoo *et al.* 2008; Comber *et al.* 2010; Carver *et al.* 2012).

Table 2.11 – Scotland's 10 'Wildest' lakes

WBID	NAME	ALT (m)	AREA (ha)	UKCOUNTY	WILDNESS SCORE
10945	Loch Uidemul	46	6.60	Na h-Eileanan an Iar	236
19371	Loch an Leóid	185	17.07	Highland	236
20512	Loch Doir' a' Chreamha	25	3.17	Highland	233
19406	Loch Dubh	188	5.66	Highland	227
14251	Fuar Loch Beag	508	3.77	Highland	221
23317	unnamed	38	2.75	Argyll and Bute	219
11660	unnamed	28	2.19	Highland	219
14350	Gorm Loch Mór	407	29.27	Highland	218
22178	Loch a' Bhealáich Bheithe	716	34.32	Highland	217
14239	Fuar Loch Mór	598	32.72	Highland	217

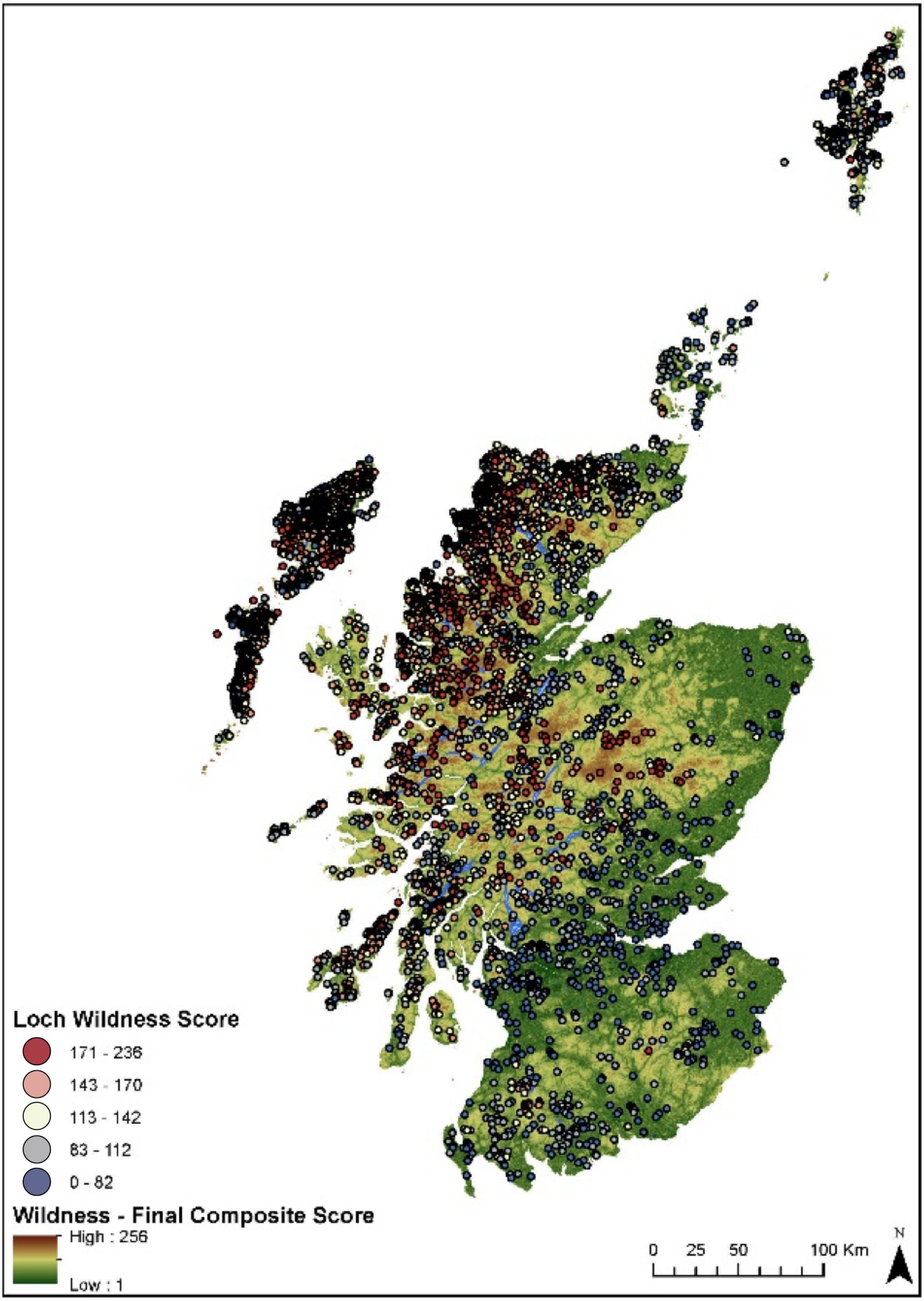


Figure 2.8 - Map of 'wildness' in Scotland from SNH composite wild land mapping. All of Scotland's lakes are scored based on this data set

2.3.4 Current condition

There are little data available on the current status of Scotland's lakes from a conservation perspective. Every SSSI is subject to the process of Site Condition Monitoring (SCM) by SNH who in the most recent cycle (2009/10) surveyed 144 standing freshwater SSSIs, 61 SACs and 11 Ramsar sites. The overall status of these surveys is broadly positive with just under 70% of SSSIs and over 90% of SACs reporting 'Favourable' condition. See Table 2.12 for full assessed and reported results. It is likely that those ecosystems in favourable condition will be most resilient to changing climate conditions (Ippolito *et al.* 2010).

The only alternative wide scale assessment of current ecological status comes from those lakes that form part of the reporting structure for the EU Water Framework Directive. 333 lakes with surface area greater than 50ha are monitored annually (see Figure 2.10 for distribution). Again the overall status result is broadly positive with 62.5% at High, Good or Good Ecological Potential status in 2012 (see Table 2.13). Over the monitoring period 2008-2011 the percentage of High and Good quality systems has remained stable, while there has been an improvement in the quality of Bad and Poor systems (see Figure 2.11). Again, those systems in good condition are likely to be more resilient to future challenges.

Using land cover mapping to estimate landscape intensity allows a national scale assessment of catchment condition. While this is not a direct link to water or ecological quality, catchments with low intensity land cover can be considered to have greater adaptive capacity than those in high intensity areas (Galbraith & Burns 2007; Weijters *et al.* 2009; Hill & Engle 2013). The results presented here (Table 2.14) demonstrate that the large majority of Scotland's lakes (76.74%) are calculated to be in low intensity catchments.

Table 2.12 – Assessed and reported condition of all standing freshwater SSSI, SAC and Ramsar sites from SNH Site Condition Monitoring reporting 2009-2010.

SSSI (No.=145)				
ASSESSED CONDITION	**No.**	**REPORTED CONDITION**	**No.**	**%**
Favourable Maintained	91	Favourable	100	68.97
Favourable Recovered	0	Unfavourable Recovering Due to Management	4	2.76
Favourable Declining	4	Unfavourable	37	25.52
Unfavourable Recovering	5	Not assessed	4	2.76
Unfavourable No change	16			
Unfavourable Declining	25			
Partially Destroyed	0			
Totally Destroyed	0			
Not Assessed	4			

SAC (NO.=61)				
ASSESSED CONDITION	**No.**	**REPORTED CONDITION**	**No.**	**%**
Favourable Maintained	55	Favourable	56	91.80
Favourable Recovered	0	Unfavourable Recovering Due to Management	0	0
Favourable Declining	0	Unfavourable	4	6.56
Unfavourable Recovering	1	Not assessed	1	1.64
Unfavourable No change	3			
Unfavourable Declining	1			
Partially Destroyed	0			
Totally Destroyed	0			
Not Assessed	1			

RAMSAR (NO.=11)				
ASSESSED CONDITION	**No.**	**REPORTED CONDITION**	**No.**	**%**
Favourable Maintained	5	Favourable	6	54.55
Favourable Recovered	0	Unfavourable Recovering Due to Management	1	9.09
Favourable Declining	0	Unfavourable	4	36.36
Unfavourable Recovering	1	Not assessed	0	0.00
Unfavourable No change	1			
Unfavourable Declining	4			
Partially Destroyed	0			
Totally Destroyed	0			
Not Assessed	0			

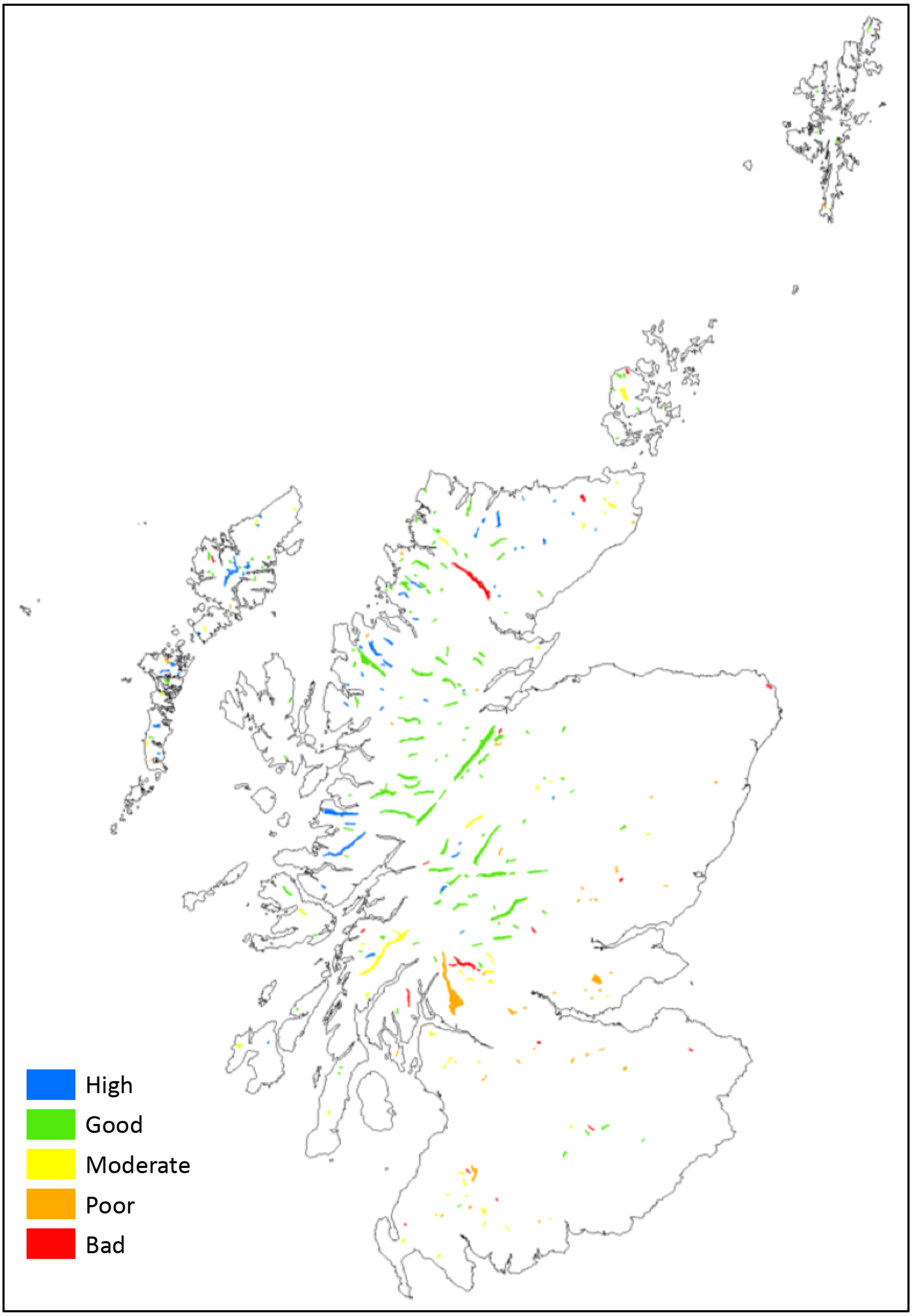


Figure 2.9 – Distribution and 2012 'Overall status' of the 333 lakes monitored under the Water Framework Directive.

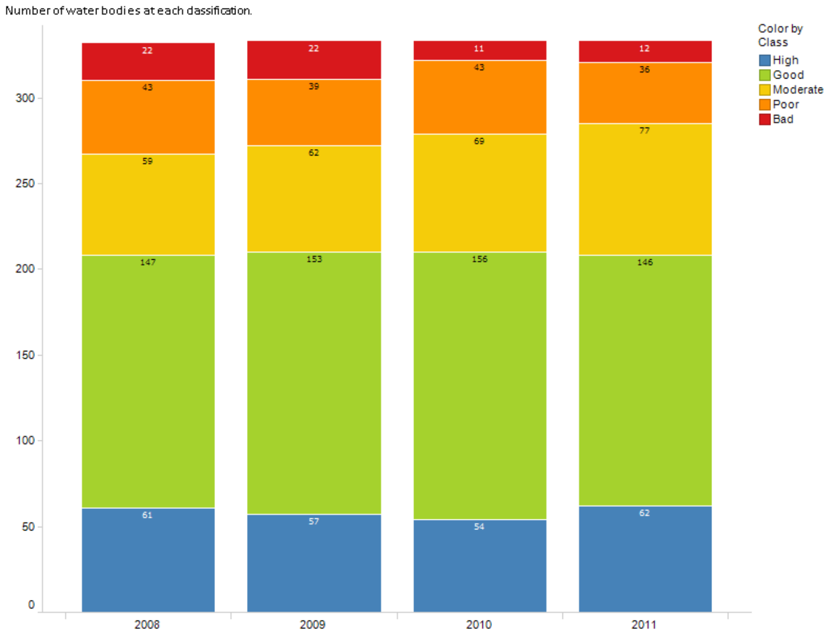


Figure 2.10 – Year on year condition data for Scotland's WFD lakes from 2008-2011 showing a steady amount of Good (green) and High (blue) quality systems and an improving situation for Bad (red) and Poor (yellow) systems becoming Moderate (orange).

Table 2.13 – WFD 'Overall status', 2012 for Scotland's monitored standing freshwaters.

WFD 2012 'Overall Status' Classification	No.	%
High	62	18.6
Good / Good Ecological Potential	146	43.8
Moderate / Moderate Ecological Potential	77	23.1
Poor / Poor Ecological Potential	36	10.8
Bad / Bad Ecological Potential	12	3.6

Table 2.14 – Results of catchment land cover intensity for all of Scotland's standing freshwaters. The large majority (77%) have low intensity land cover.

Catchment Land Cover Intensity		No.	%
HIGH	>50% CATCHMENT	606	11.73%
MID	>15% CATCHMENT	596	11.53%
LOW	<15% CATCHMENT	3965	76.74%

2.4 Discussion

Given the implications of global climate change for the natural environment, there is pressure on environmental managers to fully understand the complexity and dynamic nature of the resource base in order to be able to protect native habitats and species (Wilby *et al.* 2010; Vicente *et al.* 2013; Ausden 2014). The natural variety of lake systems and their location, landscape setting and specific catchment relations is likely to lead to some which are more sensitive and some that are more resilient in a changing environment (Dudgeon *et al.* 2006; Rowan *et al.* 2012; Carpenter *et al.* 2014; Mazziotta *et al.* 2014). Understanding this variability and increasing our baseline knowledge of the resource is a key challenge that this chapter has explored for Scotland's standing freshwaters.

2.4.1 Scotland's standing freshwater resource

Scotland undoubtedly has an outstanding standing freshwater resource but with limited data relevant across the entire resource until now the only classification systems available have been based on macrophyte species composition and measures of dissolved nutrients within a relatively small number of monitored waterbodies (Palmer & Roy 2001; Duigan *et al.* 2007; Willby *et al.* 2009; Rosset *et al.* 2013). While these indicators can give us good understanding of our systems' vegetation patterns, one of the major concerns surrounding our natural environment and climate change is that species are going to change, land uses are likely to be modified and so nutrient input to our already impacted systems will change (Jeppesen *et al.* 2005; Bierwagen *et al.* 2008; Oliver & Morecroft 2014) There is a need to look away from highly prescriptive baseline indicators such as these, towards more holistic understanding of system function (Steudel *et al.* 2012). When approaching management of such a large, widely distributed and varied resource it is impossible to produce management plans for every single site. Instead, it would be desirable to move towards a typology of lakes that considers hydromorphology as key in understanding their system function. Lakes formed in similar ways, located in similar conditions with similar catchment relations are likely to function in similar ways. In this way, management options can be targeted to enhance the resilience of the function of these lake types rather than the specific species composition of an individual site. Basic classification systems based on hydromorphological characteristics as presented (Tables 2.4-2.6) are interesting in their own right, expand our knowledge of the resource base and are useful as broad indicators of potential system sensitivity or resilience. However, they have been shown to be ineffective at finding patterns relevant for grouped management (e.g. Figure 2.6). Further work exploring these relationships with the aim of producing an ecologically relevant hydromorphological typology remains inconclusive.

2.4.2 The conservation interest: species and habitats of conservation priority

Across all classes and taxa there are species that rely on Scotland's lakes for at least part of their lifecycle. From majestic migratory Ospreys (*Pandion haliaetus)* to submerged macrophytes lakes play a vital role in the maintenance of biodiversity at the landscape scale (SNH 2006). Across this diversity there are some species that require priority or targeted management for a number of reasons: 1. Rare species that only occur in small numbers; 2. Endangered species that have suffered serious decline in population numbers; 3. Vulnerable species that may have only limited distribution; 4. Susceptible species that may have low tolerance to change; 5. Core species occurring in disproportionately large numbers and fulfilling a number of functional roles; and 6. Keystone species, which have a profound effect on ecosystem functioning (Mooij *et al.* 2005).

A feature of many lake ecosystems is their relative isolation, with a resulting tendency towards endemism. Priority species in Scotland's lakes unsurprisingly include a number of fish such as Vendace (*Coregonus albula*), Powan (*Coregonus lavaretus*) and Arctic Charr (*Salvelinus alpinus*) (Adams *et al.* 2007; Graham & Harrod 2009). These are relict populations that colonised rapidly after the last glacial maximum (c. 18,000 years ago). Much of their conservation interest derives from their subsequent biogeographic isolation, producing considerable variation in morphology, trophic ecology and life histories (Etheridge *et al.* 2010). Such species are particularly vulnerable to climate forced changes due to low tolerance of changes in water temperature and resultant changes in dissolved oxygen - with the obvious implication that alterations to key water quality and habitat dynamics may lead to local and, ultimately total, extinction in Scotland (Lyle and Maitland 2011; Elliott & Bell 2011).

In contrast, for highly mobile species, such as wetland birds, many standing waters are themselves parts of networks, or flyways, the connectivity of which is vital (Barbet-Massin *et al.* 2012; Madsen *et al.* 2014; Ausden 2014; Gillings *et al.* 2015). In such a situation, understanding the usage of a particular lake at key seasons by different populations of resident and migratory wildfowl is essential to prioritising conservation actions (Boere *et al.* 2006). Within Scotland, for example, a large number of migratory waterfowl utilise lakes at various life stages and for various means including foraging, roosting and breeding and the use of the lake itself is often linked to other features of the local landscape in which it sits. This is particularly true for important populations of geese and swans for which the lake may simply be a secure refuge amongst the landscape in which they feed (Chaichana *et al.* 2010; Huntley *et al.* 2012).

In between the extremes of the sedentary, isolated fish populations and the mobile, connected bird populations sit the vast array of other species, which must also be addressed in any comprehensive adaptation strategy. Within Scotland such species include the Great Crested Newt (*Triturus cristatus*) and Common Toad (*Bufo bufo*) both of which utilise standing waters (though often small ponds) for breeding and are easily affected by toxins, eutrophication and habitat disturbance. A number of macrophyte species are also of high conservation concern including Slender naiad (*Najas flexillis*), Shetland pondweed (*Potamogeton rutilus*) and Pillwort (*Pilularia globulifera*). Climate change effects on macroinvertebrates are still poorly known particularly where they interact with other phenomena or stressors (Durance & Ormerod 2007). However, it is likely that any effects on macrophyte and macroinvertebrate composition or density will have a subsequent effect throughout the entire system (Ormerod *et al.* 2010; Hayden *et al.* 2013). This is an area of major uncertainty and consequently we need better understandings of dispersal ability and sensitivity to change for these key structural elements in our freshwater systems (Ferna 2009; Free *et al.* 2009; Trigal-Domínguez *et al.* 2009; Domisch *et al.* 2011; Mantyka-Pringle *et al.* 2014).

The current protected area system for standing freshwaters in Scotland is built on SSSI notification where the designated feature is a trophic status descriptor based on the measure of total phosphorus (TP) in a selection of lakes. While each site has a notification process specifying the rationale for designation, it is unclear why they were originally selected, whether there was a planned network of sites or, more likely, the sites were designated ad-hoc over a number of years. 105 named lakes and a further 40 lake complexes are designated as SSSIs – out of a total of 5,165 this could be argued to be a very small sample. There have been many calls to expand protected areas to cover a minimum of 10% of all biomes (Ervin & Congress 2003; Pittock *et al.* 2009) and the current system does cover more than 13% of the entire surface area of Scotland's standing freshwaters. For standing freshwaters however surface area does not necessarily equate to conservation value and small waterbodies, disproportionately important for biodiversity, are potentially under represented in the current system (Verpoorter *et al.* 2014). There have been many recent calls to reprioritise protected areas rather than simply designating more under performing areas (Fuller *et al.* 2010; Watson *et al.* 2010; Hermoso *et al.* 2011). This approach could be key to producing a truly representative protected area network for standing freshwaters in Scotland, something which will be key to help meet the adaptation challenge ahead.

In the face of expanding threats the challenge is to upscale this further to work at a much larger scale with more full scale catchment management to increase the resilience of our standing freshwaters within the landscape. The use wildness 'scoring' is novel at this stage but may be an important factor in how landscapes are valued in the future. Whether we consider an individual lake to be a primary habitat, or part of a wider landscape assemblage, will have consequences for ways in which we are able to manage change. Allowing flux within a dynamic system might be possible at a larger ecosystem scale but is most likely untenable if we continue to attempt to manage at the site scale.

2.4.3 Current condition, landscape intensity and naturalness

It is important to understand current conditions given that climate changes will likely exacerbate current pressures and may impact more heavily on those systems which are already stressed (Bates *et al.* 2008; Noyes *et al.* 2009; Mazziotta *et al.* 2014). Results presented show a generally positive state of Scotland's standing freshwaters. For those monitored regularly over 60% of the largest lakes, annually monitored under the WFD reporting mechanism, are in Good or High condition with improvements seen over the past

5 years. For protected areas too the figure is broadly positive with just under 70% of standing freshwater SSSIs being reported in favourable condition. We have no way of knowing what condition the vast majority of our lakes are in, and it is unlikely that monitoring efforts will be expanded in the near future. Proxies for system condition, such as land cover intensity, can be useful when data is scarce (Galbraith & Burns 2007; Verburg *et al.* 2011; Oliver & Morecroft 2014). In this case over 75% of the total lake resource are reported as being in low intensity catchments, which is positive indicator of potential adaptive capacity (Bierwagen *et al.* 2008).

Not all of these lakes are entirely natural features and many have been modified over time for various purposes including abstraction for direct water supply and irrigation, for hydroelectricity generation, for the control of watercourses and flow balance as well as for recreational purposes (Rowan *et al.* 2001, 2006; Moss 2008; Elliott & May 2008; Rounsevell & Reay 2009; Lindström *et al.* 2010). The Reservoirs (Scotland) Act 2011 requires SEPA to audit all reservoirs that hold over 25,000m^3 of water. There are 662 such water bodies in Scotland and likely very many more smaller reservoirs (SEPA, 2012). While these water bodies can no longer be considered ‘natural’ many have significant conservation interest (Moss 2008; Abrahams 2008; Bresciani *et al.* 2011; Clarvis *et al.* 2013) and the direct management of these standing freshwaters could be increasingly important as part of a comprehensive adaptation plan.

2.5 Summary

The Scottish standing freshwater resource is an outstanding myriad of forms and sizes ranging across the country from the landscapes of the North West covered in small peat dominated pools, to high altitude mountain corrie lakes to expansive open waters with shallow basins and large, deep valley lakes scoured from the landscape over multiple glaciations. Lakes are found in our most densely populated urban centres and throughout the wildest of remote landscapes. This variety of form, density and distribution across the length and breadth of the country contribute not only outstanding geodiversity but also habitats of international importance for numerous species. Perhaps because of this diversity, no natural grouping of lakes were found based on simple hydromorphological categorisations for which we have full data sets.

Current conservation priority is based on a mix of species and habitats approaches, which is to be commended. In the face of expanding threats the challenge is to upscale this further to work at a much larger scale with more full scale catchment management to increase the resilience of our standing freshwaters within the landscape. The use of landscape and wildness 'scoring' is novel at this stage and without great detail, but may be an important factor in how landscapes are valued in the future. Whether we consider an individual lake to be a primary habitat, or part of a wider landscape assemblage, will have consequences for ways in which we are able to manage change. Allowing flux within a dynamic system might be possible at a larger ecosystem scale but is most likely untenable if we continue to attempt to manage at the site scale.

Chapter 3 – Exposure: Climate change in Scotland

3.1 Introduction

In the search for a climate change adaptation strategy for conservation it is vital to have a much clearer understanding of the projected impacts of climate change. Much of the ecological impact of change in particular will depend on the magnitude and rate of change (Tabor & Williams 2010; Watt *et al.* 2011). Therefore, having reliable and robust models at a spatial scale relevant to management strategies and actions is key (Mooij *et al.* 2005). For example, Burke *et al.* (2010) and Prudhomme *et al.* (2010) undertook climate change impact studies, using future climate scenario models of the UK, to assess the likelihood of drought and fluvial flood risk, respectively. Climate projection models were integrated with ecological species distribution models by del Barrio *et al.* (2006) and Gillings *et al.* (2015) to assess future range shifts and thus draw conservation conclusions. Lassalle *et al.* (2010) also combined climate and ecological models to assess future habitat suitability for the Atlantic sturgeon (*Acipenser sturio*). They found that basins along the southern limit of the range were predicted to be most strongly affected by climate change, thus allowing them to make conservation recommendations. All these studies benefited from fine-scale climate model availability to permit assessment of climate change vulnerability.

In terms of model availability, Scotland is relatively well served, with the launch in 2009 of the latest United Kingdom Climate Projections toolset (UKCP09 2011) as well as more recent global advances with the Coupled Model Intercomparison Project (CMIP5) models recently made available via WORLDCLIM (Hijmans et al. 2005) in preparation for the IPCC AR5 launch. WORLDCLIM have made available the outputs from 19 climate models used for the IPCC AR5 as well as the baseline data and data sources (weather station locations) against which the models run. This global data set is downscaled from a global circulation model (GCM) to a 30 second arc (approximately 1km^2) resolution. These models are run on four globally agreed representative concentration pathways (RCPs; Figure 1.1) developed for, but independently of, IPCC AR5 (Moss *et al.* 2008; Collins *et al.* 2011; Jones *et al.* 2011). The pathways describe four climate futures, all of which are considered possible (Jones *et al.* 2011), based on projected concentrations of greenhouse gases found in the upper atmosphere – not on emissions scenarios as before (Moss *et al.* 2008). Unlike the Special Report on Emissions Scenarios (SRES) scenarios they replace, the RCPs are not explicitly linked to social, technological, and economic storylines. Instead, they are simply plausible trends in atmospheric CO_2 (and other greenhouse gas) concentration and are named for the corresponding additional heat retained by 2100 in W/m^2. RCP 2.6 and 8.5, are the minimum and maximum emissions scenarios, respectively.

Where the CMIP5 data are made available for use by specialist climate modellers, UKCP09 is aimed at engaging stakeholders from multiple backgrounds to approach adaptation with the best possible climate data available. Based primarily on the Hadley MET Office HadRM3 model, UKCP09 is a downscaled regional climate model based on older CMIP4 climate models used for IPCC AR4. UKCP09 data provides climate projections at a $25km^2$ spatial resolution, over multiple timescales (2020s, 2050s, 2080s) and three emissions scenarios based on the SRES Scenarios – High (SRES A1FI), Medium (SRES A1B) and Low (SRES B1). More significantly, by running multiple scenarios with multiple model inputs prior to user query UKCP09 quantifies the uncertainty associated with each projection by assigning each outcome a related probability, or likelihood of occurrence (Street *et al*., 2009). UKCP09 and its predecessor UKCIP02 have been widely used for climate related studies in the UK across a range of sectors (Duncan *et al.* 2010; Jaroszweski *et al.* 2010; Burke *et al.* 2010; Prudhomme *et al.* 2010; Cloke *et al.* 2010; Rennie & Hansom 2011). The complexity of this probability based output has both been credited as allowing a robust and in depth understanding of the full range of projected changes, allowing stakeholders to plan for a wide range of outcomes, but has also been criticised for being too complex to be useful for the majority of users (Watts *et al.* 2015).

The results of both these climate change models can be mapped to show the spatial distribution of climate changes and the interrelationships between changes and features or sites of interest (Elez *et al.* 2013; Barton *et al.* 2013). Many of the expected impacts of climate change will also impact, and be mediated by, the nature of the lake catchment relation (Cloke *et al.* 2010; Staehr *et al.* 2012). Therefore, we can further analyse projections against baseline data to show more specific changes at the catchment scale, for example, by calculating potential evapotranspiration and moisture balance – important factors affecting catchment water balance and thus the hydrological function of freshwater systems (Lu *et al.*

2005; Kay & Davies 2008; Kingston *et al.* 2009). This is particularly important as changes to the hydrological function will impact on the ecology and, potentially, conservation interest, of the system.

This chapter aims to investigate how and where Scotland will be affected by climate change and what impact these changes will have on standing freshwaters. In particular, using the latest climate models, it aims to answer the following questions: 1) What are the projections of global climate change (changes to temperature and precipitation) by the middle of this century?; 2) How might exposure to these changes impact Scotland's standing freshwaters (projected temperature and precipitation and calculated PET)?; and 3) Where are the areas of greatest likely change in Scotland and which lakes are situated within these areas?

3.2 Methods

3.2.1 Data sources and analysis packages

Spatial analysis and display was completed in ArcGIS 10 (ESRI, 2011) utilizing a range of standard package and spatial analysis tools. Data and GIS Shapefiles produced for analysis as described in Chapter 2 were used including raw data and ESRI GIS shapefiles provided by SEPA and SNH under licence. Further GIS data including country and regional border shapefiles were sourced from Ordnance Survey DIGIMAP (digimap.edina.ac.uk) and the GoGeo database (http://www.gogeo.ac.uk/gogeo/).

Climate Data was sourced from two distinct climate models:

HadGEM2-ES is Hadley Centre's "standard" climate model and has been designed to run the major scenarios for the latest IPCC AR5 (Jones *et al.* 2011). HadGEM2-ES is a coupled Earth System Model which means it includes the coupled interactions of variables including the terrestrial vegetation and ocean ecosystems and gas-phase tropospheric chemistry, alongside the physical climate model (Collins *et al.* 2011; Jones *et al.* 2011). Model data are only available as high resolution *.tiff images, which can be downloaded from WORLDCLIM (http://worldclim.org) and imported as a raster data layer to ArcGIS 10. Baseline data (1950-2000) was provided by WORLDCLIM.

UKCP09 data are available online and provides a range of data outputs pre-made *.jpg and *.png graph and map images. More detailed data including *.csv for use in Microsoft Excel or R, and well as ESRI shapefiles which can be analysed in ArcGIS are output through an online 'user interface' (http://ukclimateprojections.metoffice.gov.uk/). For the purposes of this study data relating only to Scotland were downloaded directly. Baseline data (1960-1990) for this model system was provided as a raster GRID file by the UK Met Office.

3.2.2 Global Climate Change Projections

Output from the HadGEM2-ES model and WORLDCLIM Baseline data were imported to ArcGIS10 (ESRI, 2011) as raster based layers. Monthly mean data are available for three climate variables direct – Mean Temperature (◦C), Maximum Temperature (◦C) and Precipitation (mm) as well as a series of 19 'BioClim' variables which have been derived from these climate data (Booth *et al.* 2014). These include more biologically meaningful variables and these data are widely used in ecological niche modelling including MAXENT and GARP (Booth *et al.* 2014; McDowell *et al.* 2014). The BioClim variables (Bio01 – Bio19) represent annual and seasonal trends (e.g. Mean annual temperature, annual precipitation), and extreme or limiting environmental factors (e.g. Temperature of the coldest and warmest month) (Franklin *et al.* 2013; Booth *et al.* 2014).

For this study Bio01 (Mean Annual Temperature) and Bio12 (Annual Precipitation) data were mapped for both baseline (1950-2000) and 2050s (2041-2060) RCP6.0 projections. To show the absolute variation between the baseline and projection the 'Minus' tool from the 'Maths' set of Spatial Analyst toolset in ArcGIS10 (ESRI, 2011) was used to subtract the baseline values from the projections to leave a 'differential shadow' which can be mapped (Watts *et al.* 2010; Oliver *et al.* 2013).

Global projections were made more relevant to the scale of this study by mapping these outputs across the UK. Annual patterns are not the only issues which will impact on the natural environment, in fact it is likely that extremes and seasonal changes will be extremely important for both hydrology and ecology of freshwater systems (Johnson *et al.* 2009; Carvalho *et al.* 2012; Warfe *et al.* 2013). Accordingly, changes to the following variables: Bio05 (Max Temperature of the Warmest Month), Bio06 (Minimum Temperature of the Coldest Month), Bio13 (Precipitation of the Wettest Month), Bio14 (Precipitation of the Driest Month), Bio18 (Precipitation of the Warmest Quarter) and Bio19 (Precipitation of the Coldest Quarter) were utilised in this study. In addition to the HadGEM2-ES global model, ESRI shapefiles were extracted from the UKCP09 model and mapped in ArcGIS10 to show projected changes to mean summer and winter temperatures and precipitation for Scotland in the 2050s, based on a 50% probability and mid-emissions scenario. Further examples of the probabilistic outputs of the UKCP09 model are also highlighted to provide insight into the full range of projected outputs and their variability dependant on the choice of inputs to the model.

These changes to global mean annual temperature are mapped showing A) the baseline (1950-2000) mean annual temperature; B) the projected (2040-2060) temperature; and C) the difference between these two values (B minus A). Similarly, changes to extremes are e explored by mapping changes to the maximum temperature of the warmest month and the minimum temperature of the coldest month across the UK and precipitation of the wettest and driest months.

3.2.3 Climate change impacts – temperature, precipitation and potential evapotranspiration

Using the ‘Multivalues to points’ tool from the ‘Extractions’ set of the Spatial Analyst toolset in ArcGIS10 (ESRI, 2011) all of the possible data variables (Tmax, Tmean, Precip, BioClim01-19) were extracted to the lake point data for both baseline and 2050s RCP6.0 projection. Similarly monthly climate data from UKCP09 mid emissions, 50% probability temperature and precipitation models was also extracted for each lake point. Combined, these data create a comprehensive climate change database for each lake in Scotland, which can be interrogated in ArcGIS10 or exported to a simple Excel spreadsheet. Monthly values for Temperature and Precipitation were plotted for both baseline and projected changes. These values were also used to calculate potential evapotranspiration.

To associate temperature and precipitation changes more directly to their impacts on lake hydrology and ecology it is possible to calculate moisture indices for each lake in Scotland (McCabe & Wolock 2002). Moisture indices have been quantified to describe the relation between the supply of water (precipitation) and the climatic demand for water (potential evapotranspiration, PET) based solely on temperature and precipitation records or models (Murdoch *et al.* 2000; McCabe & Wolock 2002; Kay & Davies 2008). They can be directly related to important elements of catchment water balance such as runoff and are useful for large scale studies of climate variability, especially where there are difficulties calculating hydrologic changes without sophisticated catchment models which are not currently available for individual lakes (Wolock & Mccabe 1999; McCabe & Wolock 2002; Kingston *et al.* 2009). In a continental study of the conterminous USA (Wolock & Mccabe 1999) it was determined that 91% of the spatial variability of mean annual runoff was explained by the spatial variability of mean annual precipitation minus mean annual potential evapotranspiration (PMPE).

For this study, PMPE was calculated following the method described in McCabe & Wolock (2002) using the Hamon potential evapotranspiration equation (Hamon, 1961). The index quantifies the ratio between available water (based on precipitation) and evaporative demand (based on temperature and number of daylight hours). To calculate the PMPE, potential evapotranspiration (PET) was first estimated for each month during the year as follows:

$PET = 0.1651 dL W_t$

Where *PET* is measured in millimeters (mm) per month, d is the number of days in a month, L is the mean monthly hours of daylight in units of 12 hours, and Wt is a saturated water vapor density term calculated by

$Wt = 4.95e^{0.062T}$

Where T is monthly mean temperature in degrees Celsius. PET was set to zero if mean monthly temperature was below zero.

PMPE was then calculated by subtracting monthly PET from average monthly rainfall observed (WORLDCLIM 1950-2000 baseline) and projected (HadGEM2-ES 2050 RCP6.0) values, graphed to show changes throughout the year and summed to provide an annual figure for moisture balance.

3.2.4 Areas of greatest projected climate change in Scotland

To highlight those areas of Scotland that are going to experience the highest levels of change it is possible to map changes to create a simple spatial risk analysis. Using UKCP09 data at the $25km^2$ gives clear differentiation and resolvable pattern. Data were exported from UKCP09 for both 2050s and 2080s, mid emissions scenarios at 50% probability for mean temperature and precipitation projections and imported to ArcGIS10 (ESRI, 2011).

Temperature and precipitation layers were then each analysed to output the upper quartile of change from across the country. These outputs were then combined using the 'Intersect' tool from the 'Overlay' section of the 'Analysis Tools' menu in the ArcToolbox in ArcGIS10 (ESRI, 2011) to create a layer highlighting only the area of greatest projected change.

Additional information data layers relating to the lake coverage and protected area extent (see Chapter 2) were added.

3.4 Results

3.4.1 Global Climate Change Projections

Global climate projections from the HadGEM2-ES model using the RCP 6.0 2050 projection show a range of 0.6°C – 11.0°C increase to mean annual temperatures across the world (Figure 3.1). These increases are not spatially coherent – they impact some areas with greater force than others. Figure 3.2 shows the same global output reproduced for changes to mean annual precipitation. This map again shows widely differing impacts across the world, ranging from a reduction in rainfall of 1429 mm/year to an increase of 2092 mm/year. To highlight these effects across the UK these outputs are reproduced in Figure 3.3 focussed at the national rather than global level. Outputs from this model show a temperature increase from 1.1°C to 2.7°C and a precipitation change in the range of -65 mm/year to +116 mm/year.

Changes to extremes (Figure 3.5) show an increase in maximum temperatures of the warmest month of 1.4°C to 4.5°C with an increase in the minimum temperature of the coldest month of 1.0°C to 2.3°C. Precipitation of the wettest month is projected to change in the range -7 mm to +46 mm. Precipitation of the driest month is projected to change in the range -16 mm to +5 mm.

Changes to seasonality are examined in Figure 3.6 by mapping changes to the mean temperature of the warmest (+1.3°C to +3.9°C) and coldest quarters (+0.8°C to +2.2°C), the mean precipitation for the warmest (-54 mm to + 33 mm) and coldest quarters (-51 mm to +115 mm). Additionally two further Bioclim outputs are mapped which directly relate to seasonality - Temperature Seasonality variable (standard deviation*100: 168 to 756) and Precipitation Seasonality (Coefficient of Variation: -2 to 12).

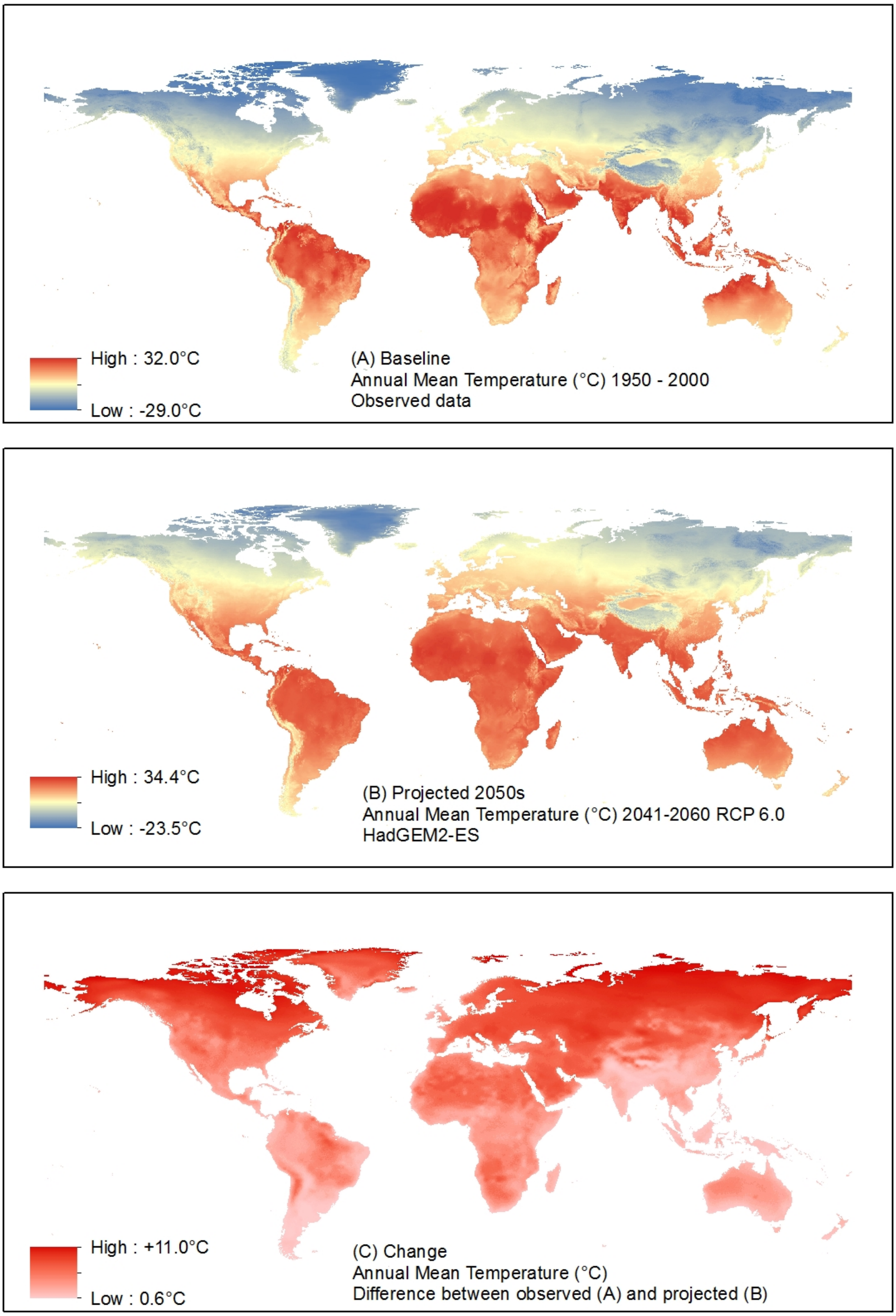


Figure 3.1 - Global Annual Mean Temperatures showing A) Baseline climate data (1950-2000); B) Climate Projections for 2050s (2040-2069) using HadGEM2-ES model RCP 6.0; and C) The overall change between A and B.

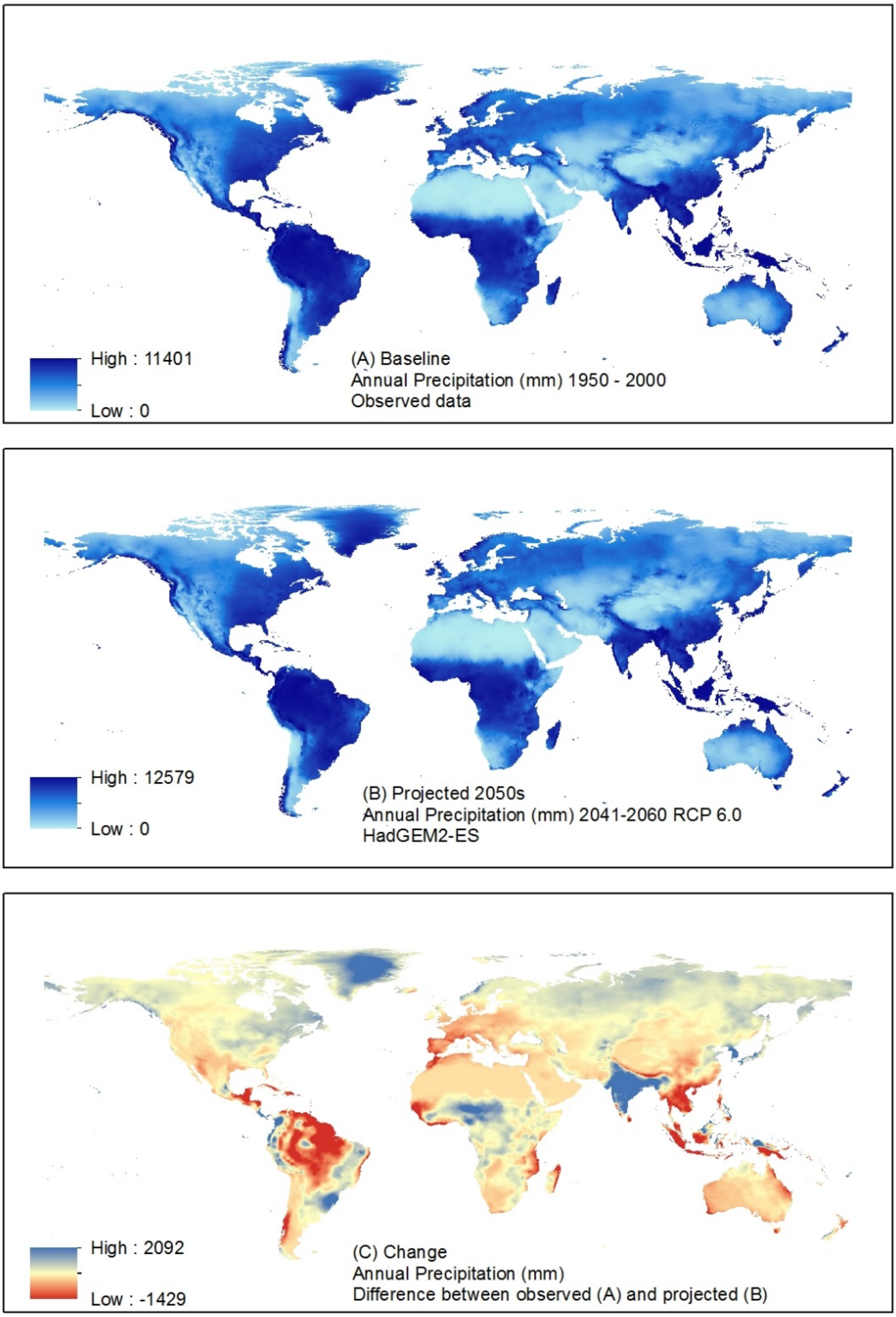


Figure 3.2 - Global Annual Precipitation showing A) Baseline climate data (1950-2000); B) Climate Projections for 2050s (2040-2069) using HadGEM2-ES model RCP 6.0; and C) The overall change between A and B.

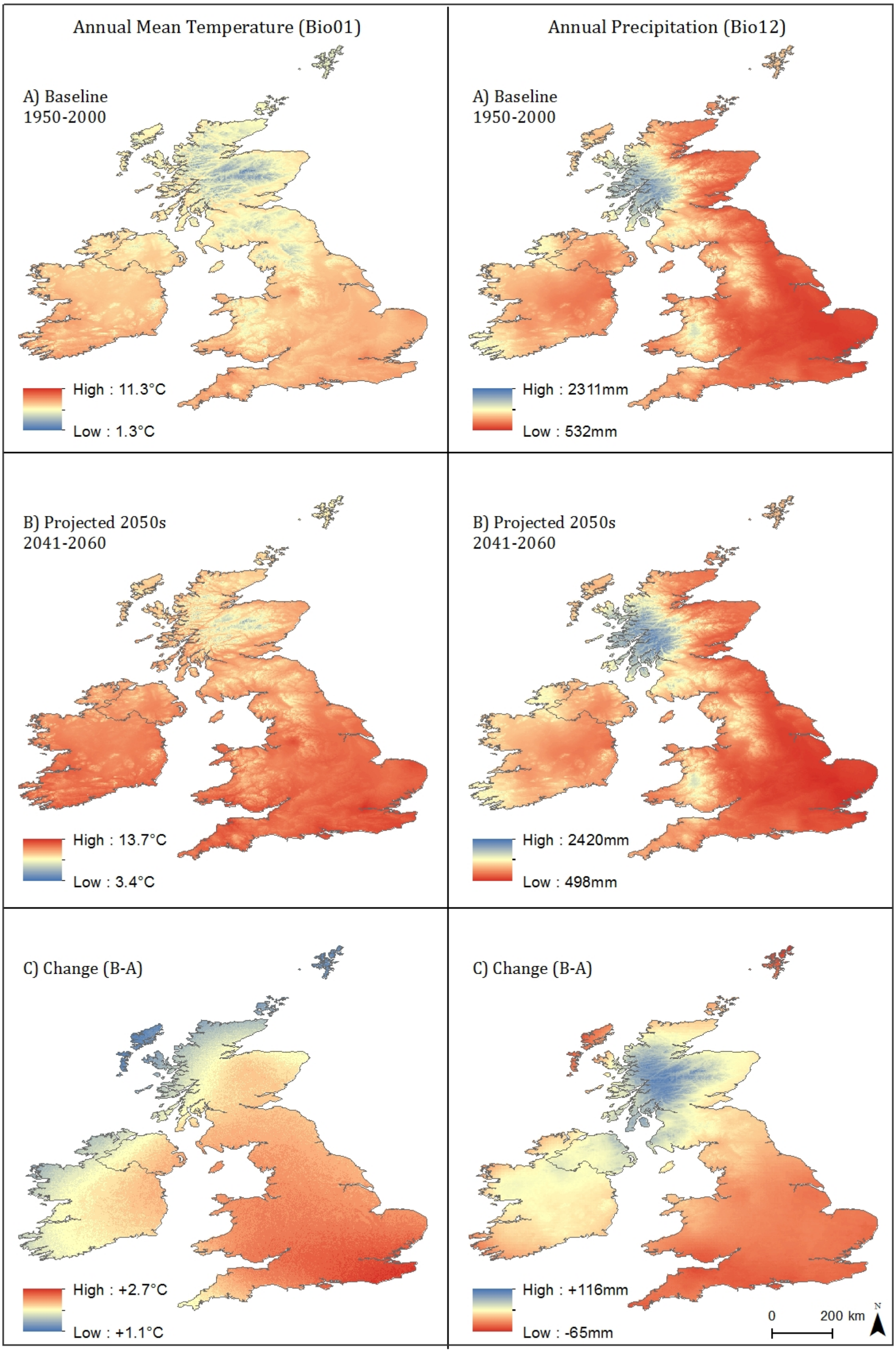


Figure 3.3 - UK Annual Mean Temperatures (left) and Annual Precipitation (right) showing A) Baseline climate data (1950-2000); B) Climate Projections for 2050s (2040-2069) using HadGEM2-ES model RCP 6.0; and C) The overall change between A and B.

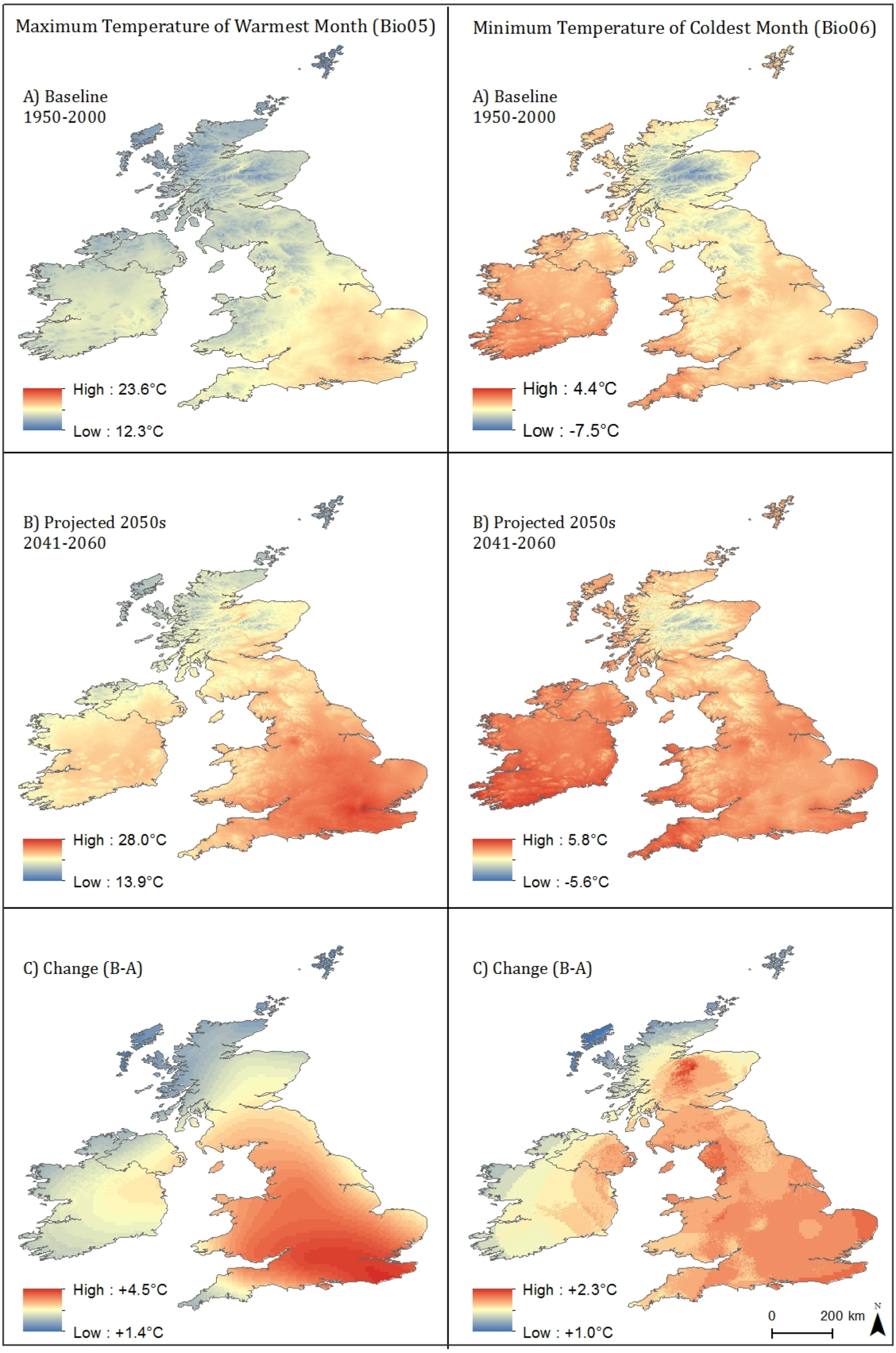


Figure 3.4 - UK Maximum temperature of the warmest month (left) and minimum temperature of the coldest month (right) showing A) Baseline climate data (1950-2000); B) Climate Projections for 2050s (2040-2069) using HadGEM2-ES model RCP 6.0; and C) The overall change between A and B.

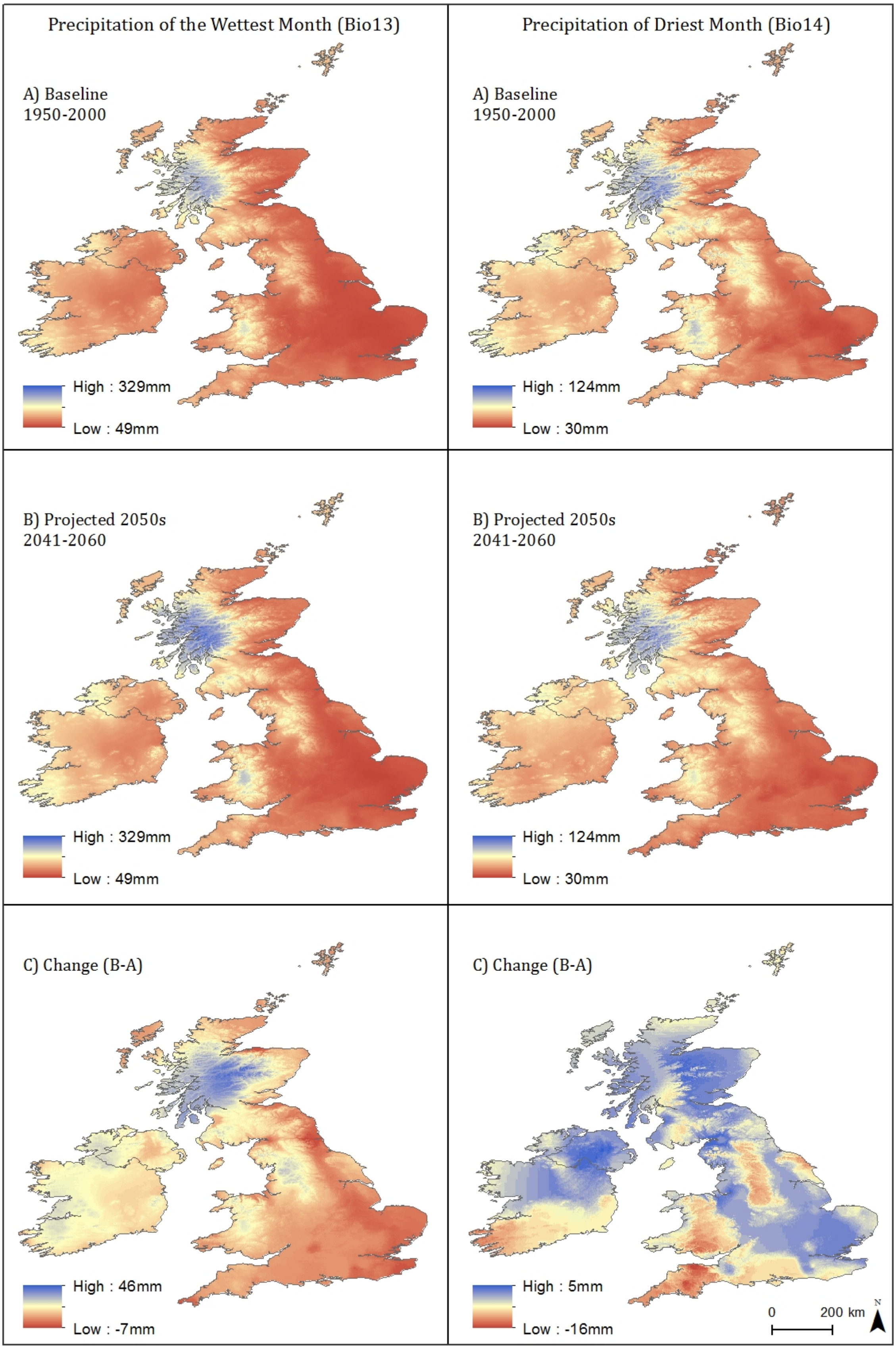


Figure 3.5 - UK Precipitation of the wettest month (left) and Precipitation of the driest month (right) showing A) Baseline climate data (1950-2000); B) Climate Projections for 2050s (2040-2069) using HadGEM2-ES model RCP 6.0; and C) The overall change between A and B.

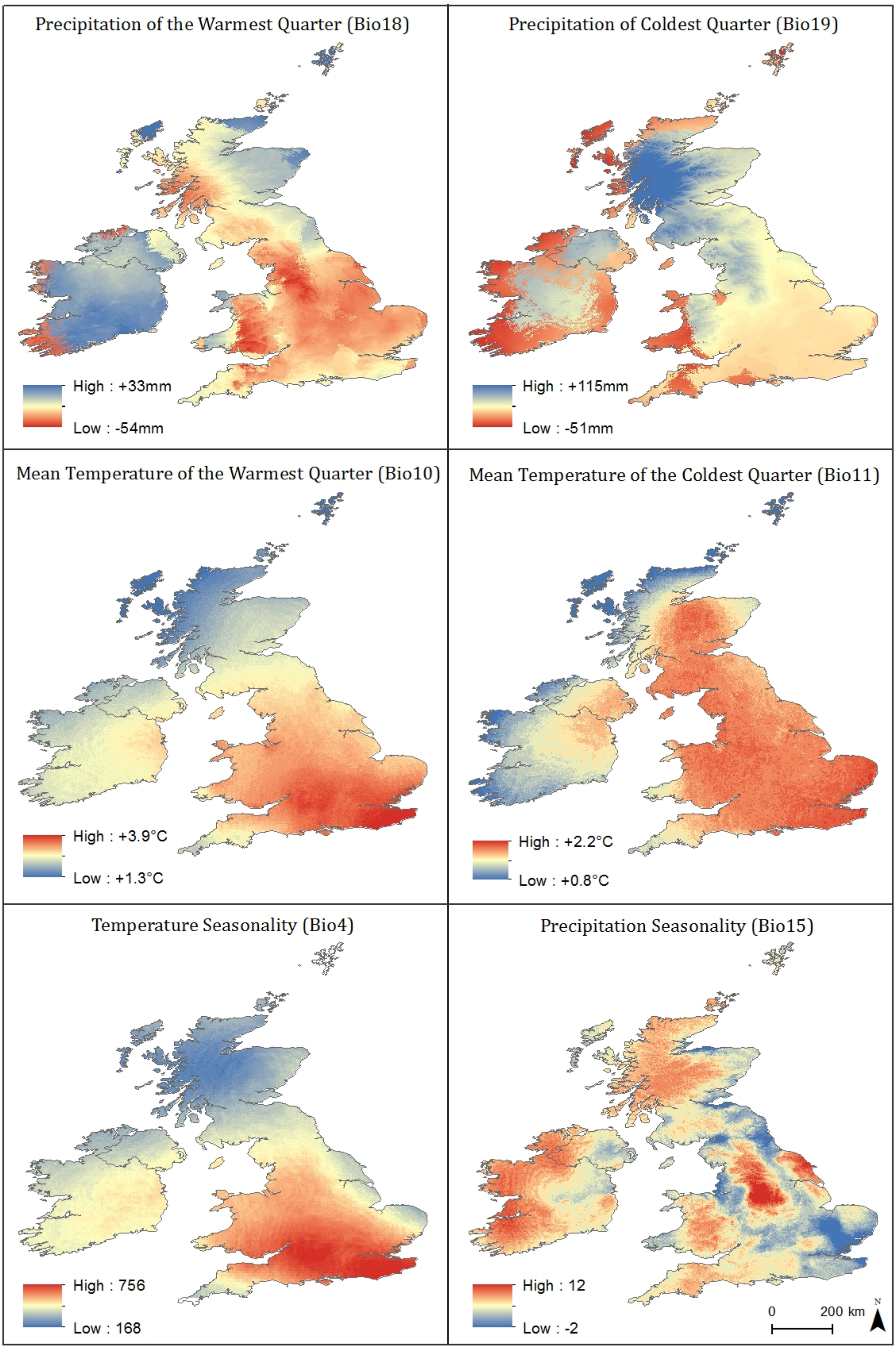


Figure 3.6 - Measures of seasonal change: difference between Climate Projections for 2050s (2040-2069) using HadGEM2-ES model RCP 6.0 and Baseline climate data (1950-2000) for Temperature and Precipitation of the warmest and coldest quarters and a Temperature and Precipitation Seasonality measures.

It is also possible to map the UKCP09 model data - Figure 3.7 shows the output of one set of data for Scotland using the regional UKCP09 2050s data. At this 25 km^2 scale, patterns indicate a South East / North West gradient across Scotland. Whilst most of the country is projected to face warmer annual mean temperatures, with wetter winters and drier summers, there are some areas, such as the Cairngorms (central highlands), which are projected to face drying throughout the year.

Making use of the probabilistic nature of the UKCP09 model output also permits exploration of a wider range of potential outcomes over the coming century. This provides a deeper understanding of the full range of projections and the opportunity to consider the uncertainty present within and between climate models. Figure 3.8 illustrates a probability density function (PDF) and a cumulative distribution function (CDF) for a 2080s projection for Scotland. These plots show the three different emissions scenarios and the relative probabilities of mean temperature change (PDF) or the likelihood of change (CDF). Figure 3.9 is a plume plot presenting data for mid emissions scenario in Scotland across the century, which gives a useful visual indication of how climate change is projected to evolve over time at key probability levels. These figures illustrate the range of projections and change over time which the use of maps alone would not allow.

Finally, Table 3.1 presents the full range of UKCP09 projection data across all emissions scenarios, time periods and probabilities for projected changes to mean summer and winter temperatures and precipitation across three regions of Scotland. The 50% mid emissions scenario as mapped in Figure 3.7 is only one value in the table which shows the full range of projections to summer temperature of +0.9°C to +4.5°C. Changes are projected to be slightly less severe in the East and North of the country. For example, 2080s mean summer temperature 50% probability shows a 2.4°C rise for the West of Scotland with 2.3°C for the East and 2°C for the North.

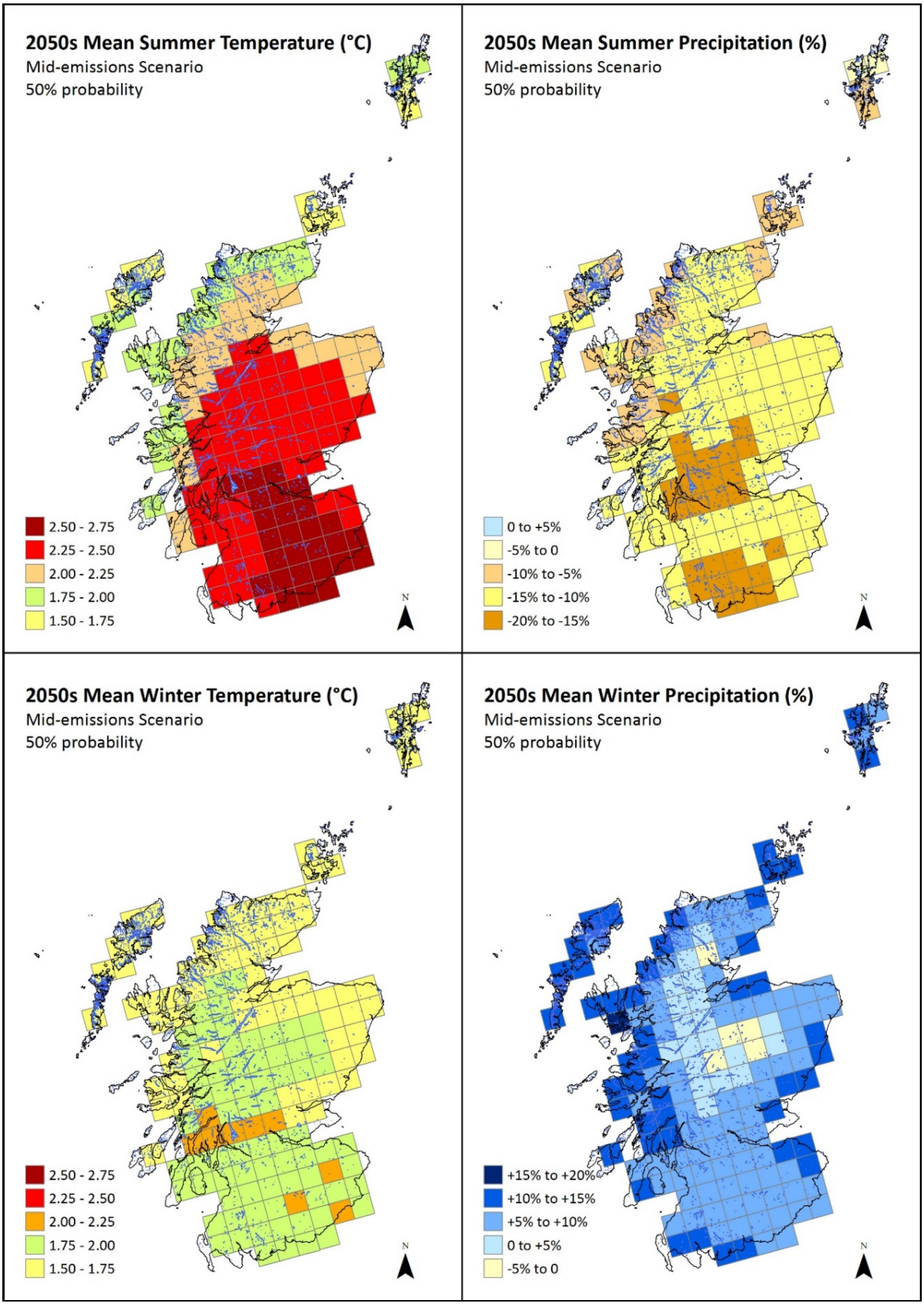


Figure 3.7 - Projected changes to mean summer and winter temperatures and precipitation are illustrated for Scotland in the 2050s, based on a 50% probability and mid-emissions scenario using UKCP09 model data.

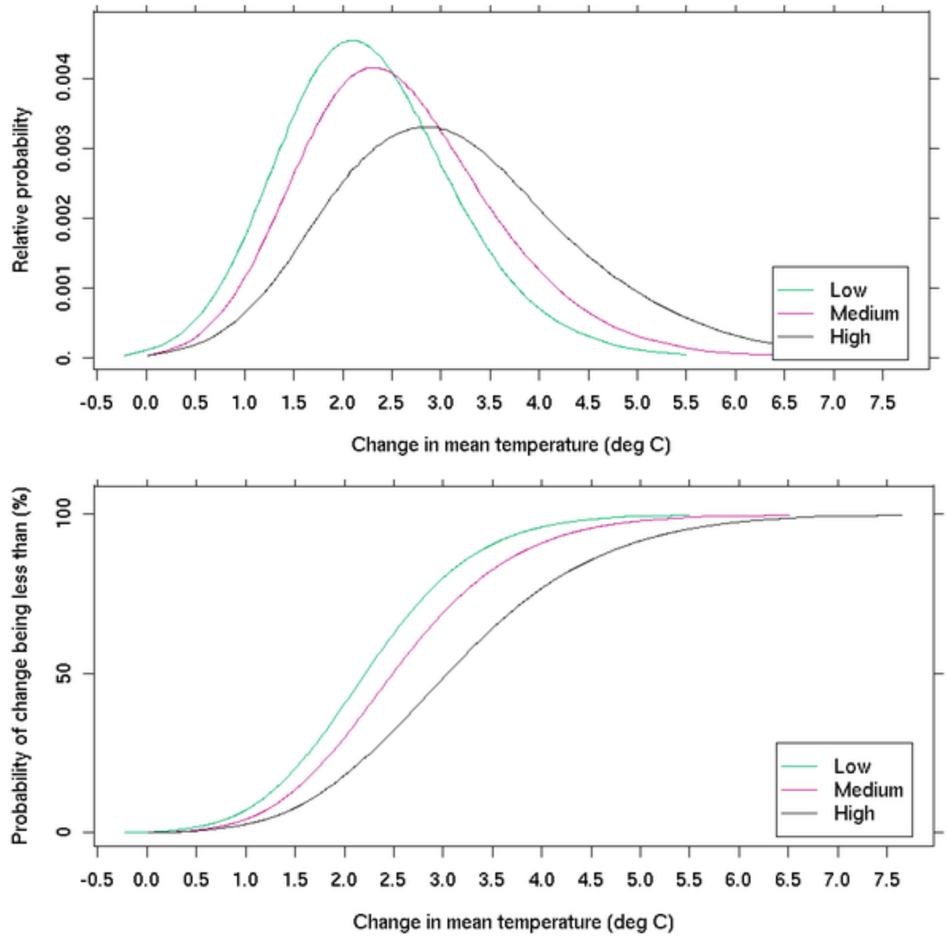


Figure 3.8 – Probability Density Function (PDF - top) and Cumulative Distribution Function (CDF – bottom) highlighting projected mean temperature change for Scotland at each emissions scenario, 2080s projection (UKCP09 data).

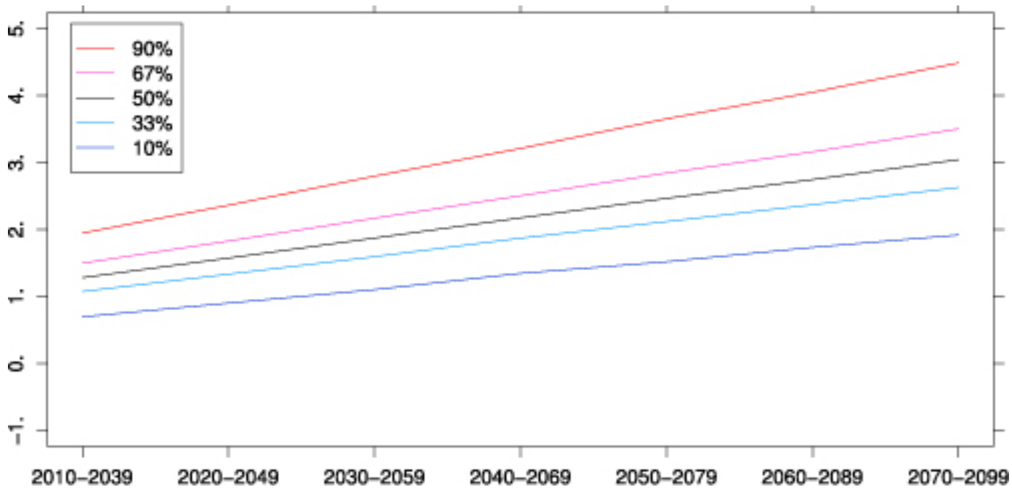


Figure 3.9 - Plume plot showing projected mean temperature change for Scotland across the upcoming century for a mid-emissions scenario at various probability levels (UKCP09 data).

Table 3.1 - Table showing the full range of climate change projections for Mean Summer/Winter changes to Temperature and Precipitation in Scotland across time periods and emissions scenarios (UKCP09 data).

			Scotland West 				Scotland East 				Scotland North 			
		Emissions Scenario	10%	50%	90%	Full range of uncertainty	10%	50%	90%	Full range of uncertainty	10%	50%	90%	Full range of uncertainty
Winter Mean Temperature	2020s	Low	0.4°C	1.2°C	2°C	0.4°C to 2°C	0.2°C	1.1°C	2°C	0.1°C to 2.1°C	0.2°C	1°C	1.9°C	0.1°C to 2°C
		Medium	0.5°C	1.2°C	2°C		0.2°C	1.1°C	2°C		0.2°C	1.1°C	2°C	
		High	0.3°C	1.1°C	2°C		0.1°C	1.1°C	2.1°C		0.1°C	1°C	2°C	
	2050s	Low	0.8°C	1.8°C	2.8°C	0.8°C to 3.3°C	0.6°C	1.6°C	2.7°C	0.6°C to 3.1°C	0.6°C	1.6°C	2.6°C	0.6°C to 3°C
		Medium	1°C	2°C	3°C		0.7°C	1.7°C	2.9°C		0.6°C	1.6°C	2.8°C	
		High	1.2°C	2.2°C	3.3°C		0.7°C	1.8°C	3.1°C		0.7°C	1.8°C	3°C	
	2080s	Low	1.3°C	2.3°C	3.6°C	1.3°C to 4.8°C	1°C	2.1°C	3.3°C	1°C to 4.2°C	1°C	2°C	3.2°C	0.9°C to 4.1°C
		Medium	1.4°C	2.6°C	4°C		1°C	2.2°C	3.7°C		0.9°C	2.2°C	3.6°C	
		High	1.9°C	3.1°C	4.8°C		1.3°C	2.6°C	4.2°C		1.2°C	2.5°C	4.1°C	
Summer Mean Temperature	2020s	Low	0.7°C	1.5°C	2.3°C	0.6°C to 2.3°C	0.7°C	1.5°C	2.4°C	0.6°C to 2.4°C	0.6°C	1.3°C	2.1°C	0.5°C to 2.1°C
		Medium	0.6°C	1.4°C	2.3°C		0.6°C	1.4°C	2.4°C		0.5°C	1.2°C	2.1°C	
		High	0.6°C	1.4°C	2.3°C		0.6°C	1.4°C	2.4°C		0.5°C	1.2°C	2.1°C	
	2050s	Low	1°C	2.2°C	3.6°C	1°C to 4.4°C	1°C	2.2°C	3.6°C	1°C to 4.5°C	0.9°C	1.9°C	4.1°C	0.9°C to 4.1°C
		Medium	1.1°C	2.4°C	3.8°C		1.1°C	2.3°C	3.9°C		0.9°C	2°C	3.4°C	
		High	1.3°C	2.8°C	4.4°C		1.3°C	2.7°C	4.5°C		1.1°C	2.4°C	3.9°C	
	2080s	Low	1.2°C	2.6°C	4.3°C	1.2°C to 6.8°C	1.2°C	2.7°C	4.5°C	1.2°C to 7°C	1°C	2.3°C	3.8°C	1°C to 6°C
		Medium	1.8°C	3.5°C	5.4°C		1.8°C	3.5°C	5.7°C		1.5°C	3°C	4.9°C	
		High	2.4°C	4.3°C	6.8°C		2.2°C	4.3°C	7°C		1.9°C	3.7°C	6°C	
Winter Mean Precipitation	2020s	Low	-3%	5%	15%	-5% to 16%	-4%	3%	11%	-4% to 12%	-3%	5%	13%	-5% to 14%
		Medium	-1%	7%	16%		-2%	4%	12%		-2%	6%	14%	
		High	-5%	5%	16%		-4%	3%	11%		-5%	4%	14%	
	2050s	Low	-1%	10%	23%	-1% to 31%	-2%	6%	15%	-2% to 20%	-1%	8%	20%	-1% to 26%
		Medium	5%	15%	29%		1%	10%	20%		3%	13%	24%	
		High	4%	16%	31%		1%	10%	20%		3%	13%	26%	
	2080s	Low	6%	20%	37%	6% to 55%	2%	11%	22%	1% to 36%	4%	16%	31%	4% to 45%
		Medium	6%	21%	42%		1%	12%	25%		4%	18%	35%	
		High	12%	30%	55%		6%	19%	36%		9%	24%	45%	
Summer Mean Precipitation	2020s	Low	-15%	-4%	7%	-17% to 8%	-15%	-5%	7%	-17% to 8%	-13%	-3%	7%	-15% to 8%
		Medium	-17%	-6%	7%		-17%	-6%	7%		-15%	-4%	7%	
		High	-14%	-3%	8%		-15%	-4%	8%		-12%	-2%	8%	
	2050s	Low	-25%	-10%	6%	-28% to 6%	-26%	-11%	6%	-28% to 6%	-21%	-8%	6%	-24% to 6%
		Medium	-27%	-13%	1%		-27%	-13%	1%		-24%	-11%	2%	
		High	-28%	-13%	2%		-28%	-13%	2%		-24%	-10%	3%	
	2080s	Low	-26%	-12%	3%	-39% to 3%	-27%	-12%	3%	-40% to 3%	-23%	-9%	5%	-36% to 5%
		Medium	-33%	-16%	1%		-33%	-17%	0%		-29%	-12%	4%	
		High	-39%	-20%	-1%		-40%	-21%	-1%		-36%	-16%	4%	

3.4.2 Climate change impacts – temperature, precipitation and potential evapotranspiration

Incorporating the climate data described above into the GIS enables detailed climate projections to be generated for each lake in Scotland (No.=5,165). An insight into the underlying data is shown for four lakes in Figures 4.10 – 4.14. These lakes were selected to highlight the impact across the country and on lakes with different hydromorphological characteristics (see Table 3.2).

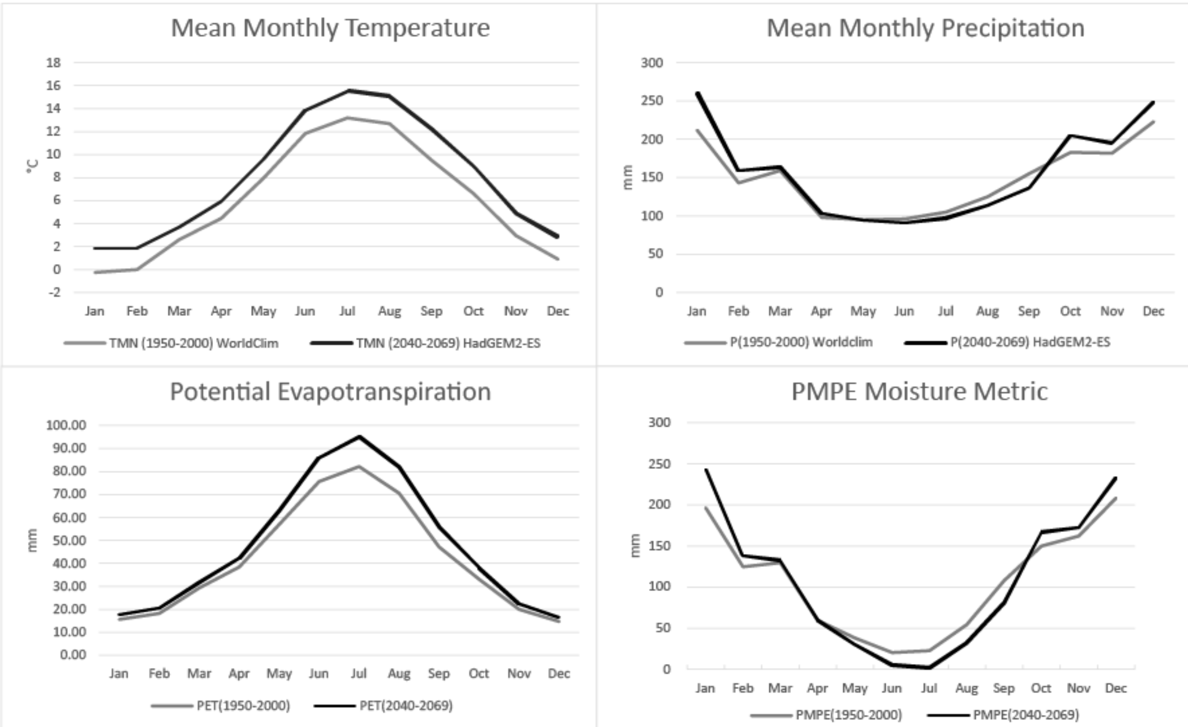
For each lake mean monthly Temperature and mean monthly Precipitation projections for 2050s from HadGEM2-ES RCP6.0 are plotted against WORLDCLIM 1950-2000 baseline data. For each of the lakes shown here mean annual temperatures are projected to rise from 1.6°C to 2.2°C with some month-to-month variation showing greater warming in summer than winter, but generally consistent warming trends across the year. Trends in mean annual precipitation vary from +20mm/yr to +93mm/yr with a great deal more variability in distribution of change. Broadly these sites show projections similar with very low levels of decreased precipitation from April to September and increases in precipitation from October to March.

Potential evapotranspiration (PET) across the four illustrated sites shows slight increases in winter with more pronounced increases in summer. The increased PET with decreased precipitation leads to projected decreases in PMPE moisture balance with three sites (Kingside Loch, Loch Maree and Loch of Kinnordy) entering prolonged periods of moisture deficit in the summer months. Changes of this magnitude are likely to change water temperatures, disrupt stratification patterns and increase chances of algal blooms amongst other factors significantly affecting the hydrology and ecology of the system (Johnson *et al.* 2009; Spears *et al.* 2012; Moss 2014).

Table 3.2 - Outline characteristics of four Scottish Lakes chosen to display in depth climate change impact data.

Loch Name	UK County	Altitude (m)	Surface Area (ha)	Alkalinity	Mean Depth	HMT	SSSI Designation
Loch of Kinnordy	Angus	146	17.41	HA	Sh	10	Eutrophic loch
Loch Maree	Highland	6	2797.56	LA	D	3	Oligotrophic loch
Kingside Loch	Scottish Borders	348	6.23	MA	Sh	8	Oligotrophic loch
Loch an Daimh	Perth and Kinross	433	280.91	MA	Sh	1	-

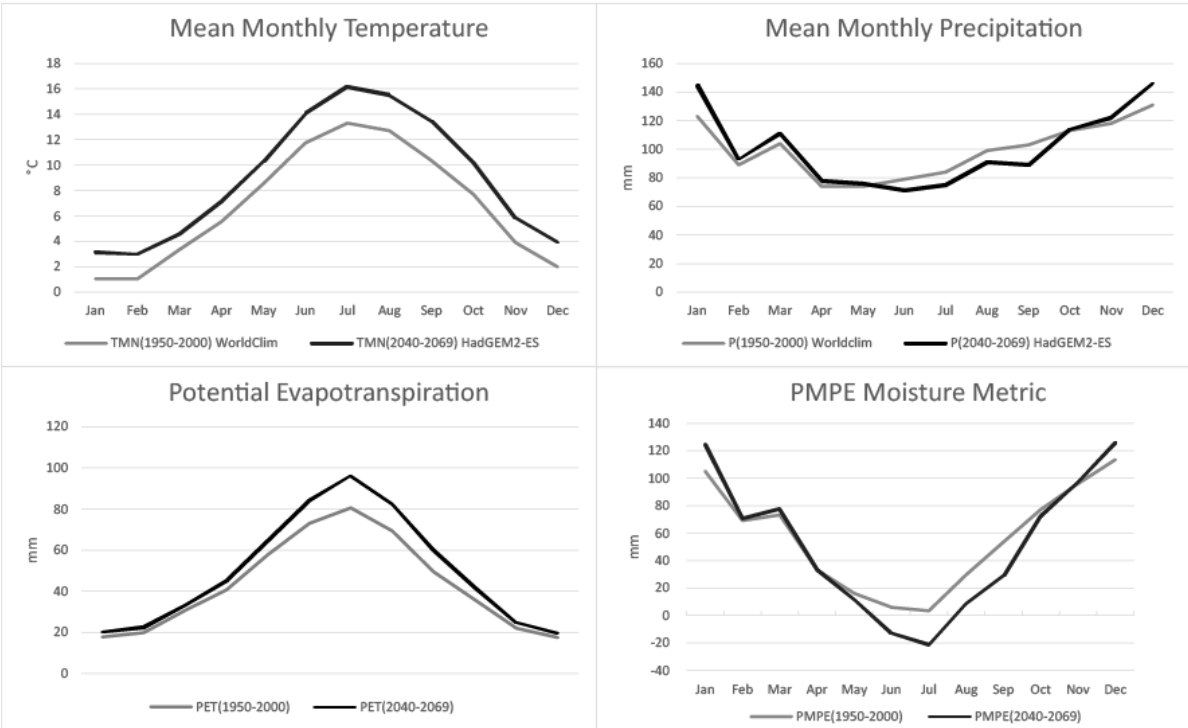
WBID	23465	*Size*	L (281ha)
Protected Area Status	-	*HMT*	1
Alk	MA	*Catchment Area*	2710ha
Mean Depth	Sh (<15m)	*Loch:Catchment Ratio*	0.1
Altitude	High (433m)	*Max altitude in catchment*	925m



	Baseline (1950-2000)	*2050's (2040-2069)*	*Change*
Annual Mean Temperature (°C)	6.0	8.0	+2.0
Max Temperature of Warmest Month (°C)	17.1	19.8	+2.7
Min Temperature of Coldest Month (°C)	-3.0	-1.1	+1.9
Annual Precipitation (mm)	1776	1869	+93
Precipitation of Wettest Month (mm)	223	261	+38
Precipitation of Driest Month (mm)	95	91	-4

Figure 3.10 – Climate change impacts to Loch an Daimh, a large, high altitude, shallow lake in Perth and Kinross. Baseline figures from WORLDCLIM 1950-2000 observed climate data and projected changes from HadGEM2-ES RCP 6.0 model.

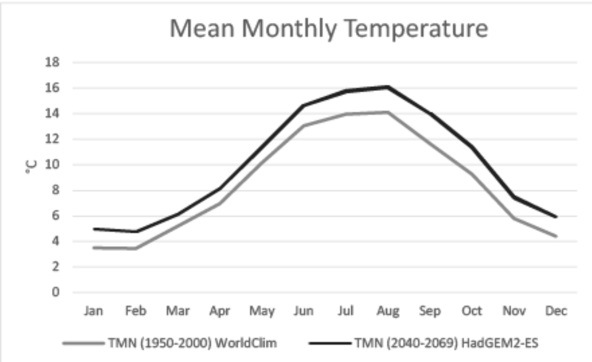
WBID	27476	*Size*	VS (6.23ha)
Protected Area Status	SSSI, Oligotrophic Loch	*HMT*	8
Alk	MA	*Catchment Area*	62.5ha
Mean Depth	Sh (<15m)	*Loch:Catchment Ratio*	0.09
Altitude	Mid (348m)	*Max altitude in catchment*	383m

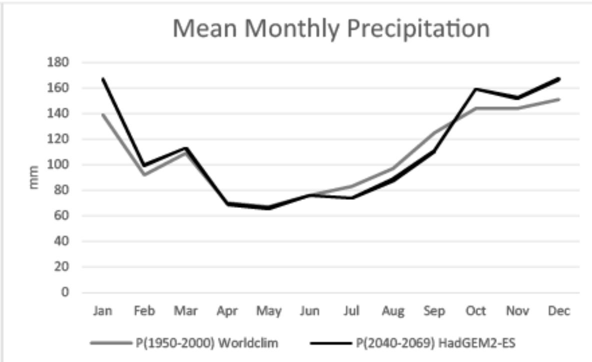


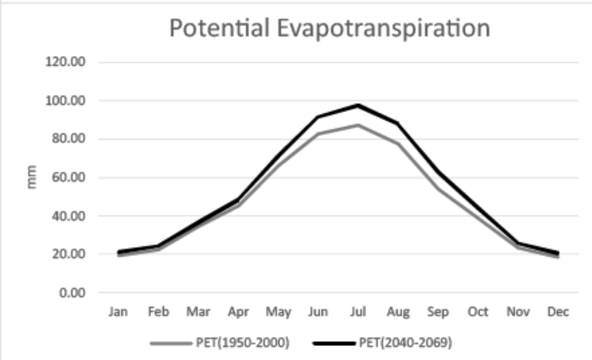
	Baseline (1950-2000)	*2050's (2040-2069)*	*Change*
Annual Mean Temperature (°C)	6.7	8.9	+2.2
Max Temperature of Warmest Month (°C)	17.6	20.9	+3.3
Min Temperature of Coldest Month (°C)	-1.9	0.0	+1.9
Annual Precipitation (mm)	1991	1211	+20
Precipitation of Wettest Month (mm)	131	146	+15
Precipitation of Driest Month (mm)	74	71	-3

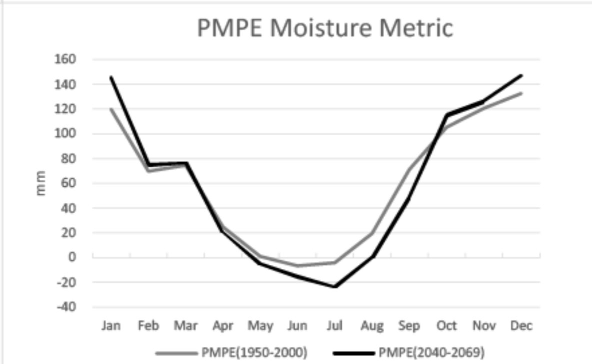
Figure 3.11 - Climate change impacts to Kingside Loch, a very small shallow lake in the Scottish Borders. Baseline figures from WORLDCLIM 1950-2000 observed climate data and projected changes from HadGEM2-ES RCP 6.0 model.

WBID	14057	*Size*	L (2055ha)
Protected Area Status	SSSI, Oligotrophic Loch	*HMT*	3
Alk	LA	*Catchment Area*	44011ha
Mean Depth	D (>15m)	*Loch:Catchment Ratio*	0.06
Altitude	Low (6m)	*Max altitude in catchment*	980m





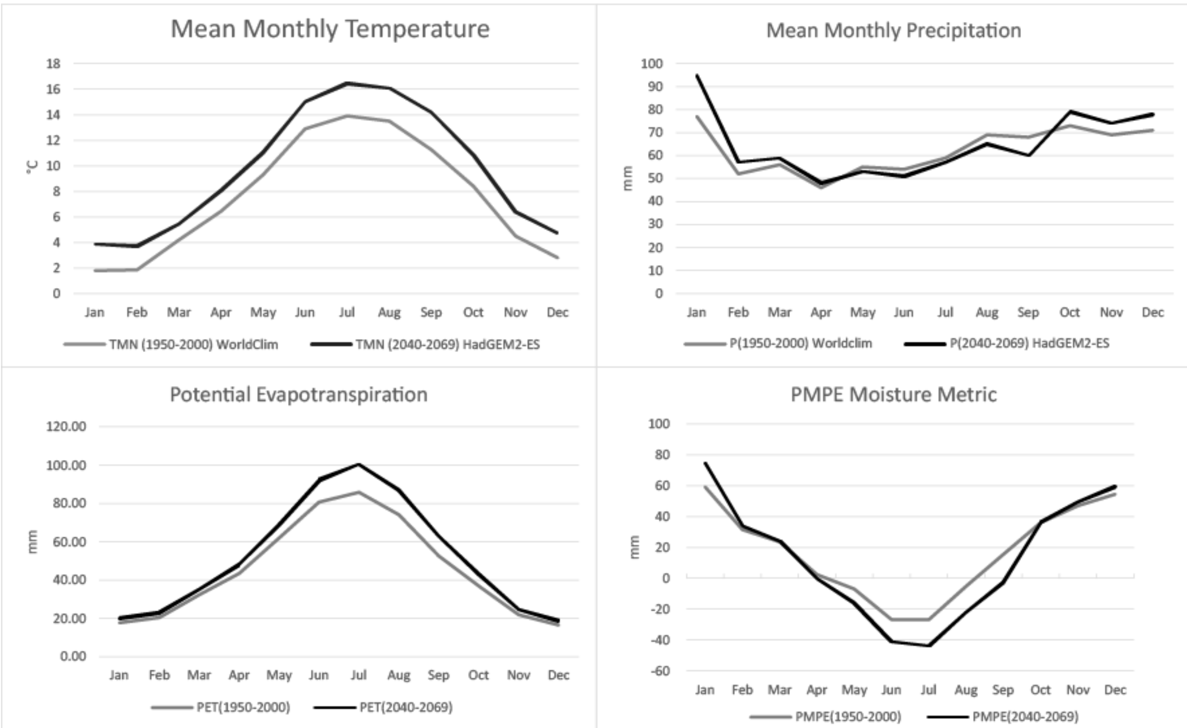




	Baseline (1950-2000)	*2050's (2040-2069)*	*Change*
Annual Mean Temperature (°C)	8.4	10.0	+1.6
Max Temperature of Warmest Month (°C)	17.3	19.4	+2.1
Min Temperature of Coldest Month (°C)	0.6	2.0	+1.4
Annual Precipitation (mm)	1297	1341	+44
Precipitation of Wettest Month (mm)	151	167	+16
Precipitation of Driest Month (mm)	67	66	-1

Figure 3.12 – Climate change impacts to Loch Maree, a large deep lake in the North West Highlands. Baseline figures from WORLDCLIM 1950-2000 observed climate data and projected changes from HadGEM2-ES RCP 6.0 model.

WBID	23024	*Size*	VS (17.4ha)
Protected Area Status	SSSI, Eutrophic Loch	*HMT*	10
Alk	HA	*Catchment Area*	109ha
Mean Depth	Sh (<15m)	*Loch:Catchment Ratio*	0.15
Altitude	Low (146m)	*Max altitude in catchment*	172m



	Baseline (1950-2000)	*2050's (2040-2069)*	*Change*
Annual Mean Temperature (°C)	7.6	9.6	+2.0
Max Temperature of Warmest Month (°C)	18.1	21.0	+2.9
Min Temperature of Coldest Month (°C)	-1.3	0.5	+1.8
Annual Precipitation (mm)	749	776	+27
Precipitation of Wettest Month (mm)	77	95	+18
Precipitation of Driest Month (mm)	46	48	+2

Figure 3.13 - Climate change impacts to Loch of Kinnordy, a very small eutrophic lake in Angus. Baseline figures from WORLDCLIM 1950-2000 observed climate data and projected changes from HadGEM2-ES RCP 6.0 model.

3.4.3 Areas of greatest projected climate change in Scotland

To help environmental managers prioritise action it can be useful to conduct a basic spatial risk analysis (Williams *et al.* 2008; Tabor & Williams 2010; McClure *et al.* 2013). Such analyses can take many forms but generally involve overlaying climate data with habitat or species distribution data (Pearson & Dawson 2003; Phillips *et al.* 2006; Munang *et al.* 2010; Huntley *et al.* 2012). Here a simple approach is used to highlight those areas likely to face the greatest change in Scotland across a range of scenarios over the coming century.

Figure 3.14 illustrates the areas of greatest change using the 2050s, mid emissions, 50% probability scenario. In this scenario the area highlighted in the orange boxes are projected to face +2.5°C to +2.75°C increases to mean summer temperatures coupled with -15% to -20% decrease to precipitation over the summer months. There are 201 lakes within this area of greatest change, 16 of which are currently designated as SSSIs. These include some areas of national importance including Loch Lomond – the heart of the Loch Lomond and Trossachs National Park.

Figure 3.15 illustrates an extreme scenario: 2080s, high emissions scenario, 50% probability. In this scenario the areas highlighted in red are projected to face >4.5°C and >20% decrease in precipitation over the summer months. Within this area there are 160 lakes, 11 of which are currently designated as SSSIs, and again include high profile areas and lakes in the heavily populated central belt area of the country that may be under other pressures as well. If known, distributions of other species or habitats of conservation concern could be added to this GIS output to create more comprehensive maps of utility for managers (Duputié *et al.* 2014).

The characteristics of those lakes within the 2050 area (Figure 3.14) are outlined in Table 3.3. Of particular note here are 'Marl' and 'High Alkalinity' lakes as 20% and 22% respectively of the national resource fall within the high risk zone. It is also interesting to note the high percentages of impacted lakes (with 'Poor' or 'Bad' WFD 'Overall Status') already within this zone. Given that climate change impacts will likely exacerbate current pressures, management of these lakes will continue to be a major challenge (Wilby *et al.* 2006).

Table 3.3 - Summary characteristics of Scotland's standing water resource and current WFD overall status for Scottish lakes subject to routine monitoring highlighting the number of lakes which fall within the projected 2050 high risk zone (see Figure 3.14)

	Total Resource	2050 high-risk zone	% of category
Lake Characteristic	**N = 5167**	**N = 388**	
Surface area			
Very Small (2–10 ha)	3624	239	7
Small (10–50 ha)	1205	107	9
Large (50+ ha)	338	42	12
Mean depth			
Very Shallow (<3 m)	225	24	11
Shallow (3–15 m)	4878	359	7
Deep (>15 m)	64	5	8
Altitude			
Low altitude (<200 m asl)	3664	249	7
Mid altitude (200–400 m asl)	1148	139	9
High altitude (400 m+ asl)	355	0	0
Alkalinity			
Marl	54	11	20
Brackish	36	2	6
Peat	737	9	1
Low Alkalinity	2407	126	5
Mid Alkalinity	1278	96	8
High Alkalinity	655	144	22
WFD 'Overall status' class	**N = 340**	**N = 43**	
High	61	0	0
Good / Good Ecological Potential	150	9	6
Moderate / Moderate Ecological Potential	68	15	22
Poor / Poor Ecological Potential	43	14	33
Bad / Bad Ecological Potential	18	5	28

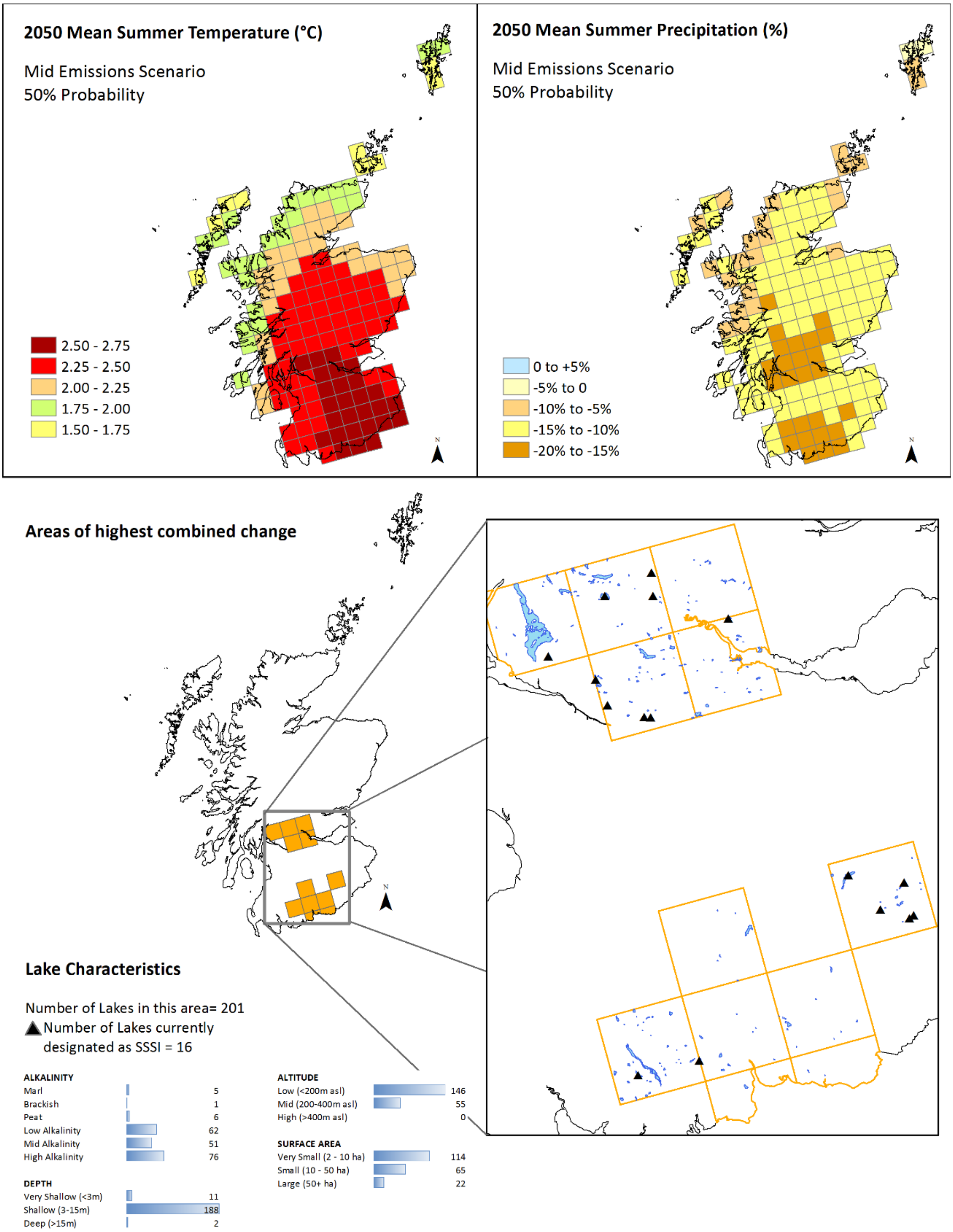


Figure 3.13 - Mapping intersection of those areas projected to experience the greatest change to both mean summer temperature and mean summer precipitation (UKCP09 2050s, mid emissions scenario, 50% probability). 201 lakes, 16 currently designated as SSSI fall within this area.

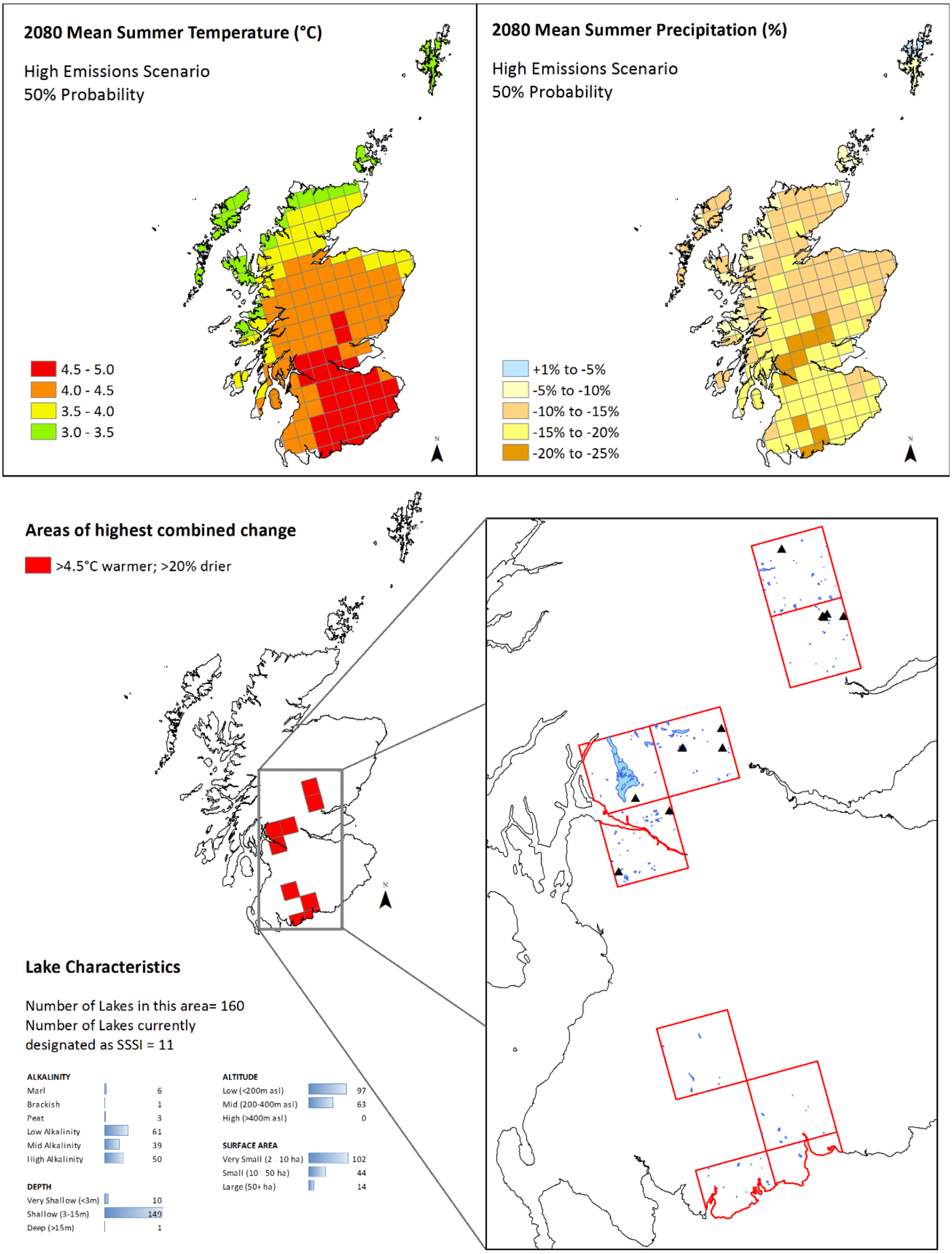


Figure 3.14 - Mapping intersection of those areas projected to experience the greatest change to both mean summer temperature and mean summer precipitation (UKCP09 2080s, high emissions scenario, 50% probability). 160 lakes, 11 currently designated as SSSI fall within this area.

3.5 Discussion

The results presented show a clear projection of change to Scotland's climate over the coming century using two distinct model systems. Projected changes to global climate have been shown to impact on the UK and Scotland using both the UKCP09 and HadGEM2-ES climate models. Projections show a change in mean annual temperature in the range of 0.6°C to 11.0°C (see Figure 3.1) by the 2050s. This is likely to impact the UK in the range 1.1°C to 2.7°C. Precipitation too is projected to change, with annual projections in the UK from -65 to +116 mm/yr.

3.5.1 Global Climate Change Projections

Despite the weight of climate change evidence (Bates *et al.* 2008; Heino *et al.* 2009; Wilby *et al.* 2010; Dawson *et al.* 2011; Kreyling *et al.* 2013; Snover *et al.* 2013; IPCC 2014; Harrison *et al.* 2015), there remains uncertainty implicit in any modelling process (Kingston *et al.* 2009; Beven & Alcock 2012). Modelling uncertainty arises from our incomplete understanding of the climate system and the inability of climate models to represent the real system perfectly and is further compounded by the downscaling of models from global to local scales (Murphy *et al.* 2010). Further uncertainty arises from natural climate variability from year to year and decade to decade due to internal dynamical and physical processes in the climate system. Climate change is superimposed onto this variability, and will potentially modify some of its characteristics (Kreyling *et al.* 2014). Finally, it is not possible to be sure how human inputs to the global system will be modified over the coming years, nor what feedbacks or kickbacks may occur naturally (Folke & Rockström 2009; Charlesworth & Okereke 2010; Jackson 2011; European Environment Agency 2012; Wise *et al.* 2014). Model choice is therefore important as different models have different assumptions inbuilt and can give different results (Tabor & Williams 2010).

Here, two models were used to provide a) a regional ensemble model, providing a wide ranging probabilistic output downscaled specifically to the UK (UKCP09) and b) a more spatially explicit, state of the art global earth system model (HadGEM2-ES). The HadGEM2-ES model has a superior spatial resolution (~1km^2 vs 25km^2) and uses more complete coupled earth system models, which allow us to produce locally defined outputs. HadGEM2-

ES uses a longer baseline period (1950-2000; Figure 1.2) so change is more realistic based on what we understand to be our climate now. HadGEM2-ES only gives one output for each Representative Concentration Pathway however. This could be argued as being easier to understand and therefore more useful to cross the science – policy gap (Christoff 2010; Game *et al.* 2011; Cook *et al.* 2013) but it could mean missing the breadth of range which probabilistic UKCP09 output provides. Allowing a full range of forecasts could allow managers to plan better for uncertain futures (Adger *et al.* 2005; Kass *et al.* 2011). Both models are freely available but where the UKCP09 interface allows quick access to a range of projections and numerous pre-produced maps and outputs, and so can easily be used by a wide range of stakeholders (Street *et al.* 2009), HadGEM2-ES requires relatively advanced GIS skills. Both models have come from legitimate sources which is important for policy maker 'buy in' (Lemieux & Scott 2011). A further advantage of HadGEM2-ES is that it is, by definition, also a global data set so other regions could use directly comparable climate data if desired for similar studies in the future.

These models provide very similar outputs – Fig 3.16 shows 2050 projections for Kingside Loch for both HadGEM2-ES (RCP6.0) and UKCP09 (Mid emissions, 50% probability) models, for both baseline and projected figures. The HadGEM2-ES data presents slightly higher temperatures throughout the year for both the baseline and projected data. Given all of these considerations we can be confident that using HadGEM2-ES is the best choice for sensitivity and vulnerability assessment in the UK given its more recent earth system coupled data input, longer baseline and higher spatial resolution and global data set.

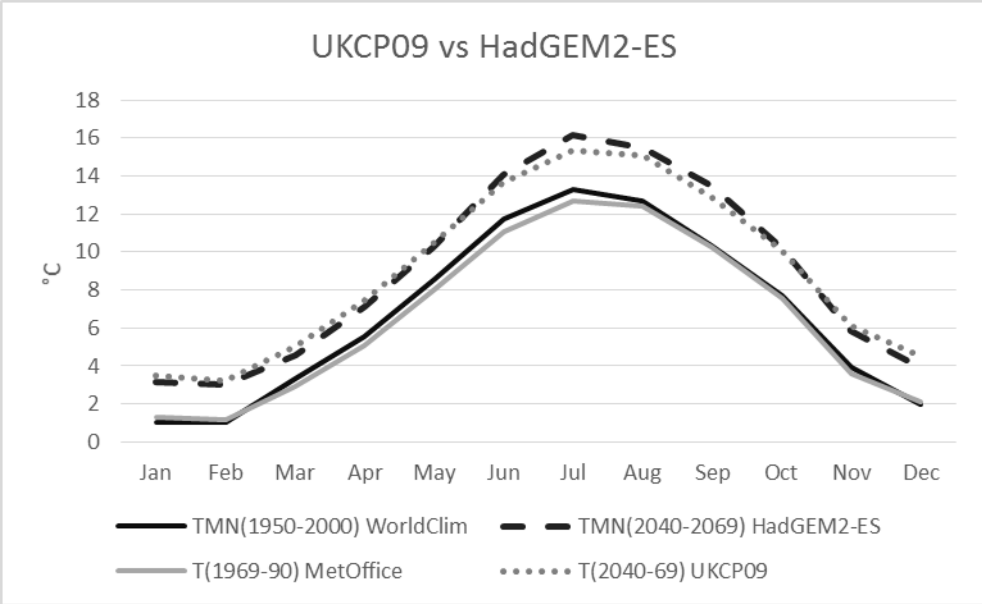


Figure 3.15 - A comparison of climate model outputs for one location in Scotland (Kingside Loch, SSSI). Both the baseline and projected output for the WORLDCLIM/HadGEM2-ES (RCP 6.0) model show a slightly warmer mean monthly temperature to the MetOffice/UKCP09 (mid emissions, 50% probability) outputs.

3.5.2 Climate change impacts – temperature, precipitation and potential evapotranspiration

Downscaling climate models for use by environmental managers concerned with the impacts of change on hydrology and ecology of individual sites is a further challenge due to the complex relationships between each individual lake and its catchment, hydrology and land use (Galbraith & Burns 2007; Weijters *et al.* 2009; Maberly & Elliot 2012). Furthermore, these climate models do not directly address indirect impacts of change such as the impacts of land use change (Watt *et al.* 2011) and other model variables (e.g. wind speed, snow melt, ice duration, cloud cover, humidity). While there are options within UKCP09 to explore these variables it was not included in the analysis as the outputs are currently unreliable (Street, Haggs and Harding, personal communication). Change to all of these climate variables will likely have a strong effect on the hydrology and ecology of lake systems. However, until models of these variables improve we can't begin to approach the whole system impacts of climate change.

To give some insight into the potential impact of the changes to temperature and precipitation to lake hydrology, Potential Evapotranspiration (PET), an important factor affecting catchment water balance, was calculated which allowed a simple moisture metric to be calculated to show change in monthly and annual water balance (Wolock & Mccabe 1999; McCabe & Wolock 2002; Kingston *et al.* 2009). This metric does not account for changes in surface runoff or groundwater recharge so cannot provide a full account of catchment water balance, but it does give a clear indication of the potential changes to water balance, in particular summer months with potential water scarcity or deficit, which is likely to impact upon both the hydrology and ecology of these systems (Whitehead *et al.* 2009; Falloon & Betts 2010; Shuter *et al.* 2012).

3.5.3 Areas of greatest projected climate change in Scotland

One way to highlight the potential threats climate change poses to our natural habitats is to undertake a form of spatial risk assessment (Tabor & Williams 2010; McClure *et al.* 2013). By mapping those areas of Scotland projected to face the greatest change to mean summer temperatures and precipitation we can prioritise action based on the geography of change rather than on the direct or indirect impacts of change itself. This should only be considered a guide, but at a broad scale it is useful to highlight potentially high risk areas to policy makers. There are limitations to these maps including the ability to display only a single model choice (as opposed to multiple probabilities) and to the availability of species distribution data to include. However, the display of these high risk areas, and the easily understood and processed visual nature of the maps (e.g. Figures 3.14 and 3.15) is potentially useful and important for environmental managers faced with taking action with limited time and resources (Wilby *et al.* 2010; Oliver *et al.* 2013). This of course does not mean that habitats and species occurring outwith this area are not vulnerable to change, but simply that this is the area of greatest change. Here, the aim is to highlight those areas of highest risk as a means of focussing early conservation action (Hopkins *et al.* 2007; Dawson *et al.* 2011; Game *et al.* 2011).

Given the range of projections, having clear indication that there will be change is key here for engaging adaptation action. We do not yet know what difference a change of +2.5°C will cause as opposed to a change of +2.8°C, but it is very likely that larger changes will have bigger consequences (European Environment Agency 2012; Dokulil 2013; Oliver *et al.* 2013).

Further work on the sensitivity of standing freshwater habitats to climate change is needed and subsequently a more complete vulnerability assessment can be undertaken (see Chapter 4) to highlight those areas where adaptation actions could be targeted.

3.6 Summary

This chapter set out to investigate the impacts of global climate change in Scotland. Projected changes to global climate have been shown to impact on the UK and Scotland using both the UKCP09 and HadGEM2-ES climate models. Global Projections show a change in mean annual temperature in the range of 0.6°C to 11.0°C (see Figure 3.1) by the 2050s. This is likely to impact the UK in the range 1.1°C to 2.7°C with a clear South-East/North-West gradient (see Figure 3.7). Precipitation too is projected to change, with annual projections globally of change from -1429 mm/yr to +2092 mm/yr. In the UK this range is again less extreme with annual precipitation varying from -65 to +116 mm/yr.

Changes will not be universal year round and extremes of temperature and precipitation are very likely to increase, both in terms of long term averages and short term extreme events (Bates *et al.* 2008; Wilby *et al.* 2010; Watts *et al.* 2015). Whilst there are potential issues with all climate models and with those variables we are currently able to reliably model, it is clear that Scotland is going to face unprecedented change over the coming century. Mapping these climate projections allows clear visual interpretation of the data downscaled to the UK and Scotland in particular. By incorporating the climate model data into a GIS we can further interrogate the results for specific locations.

Such analysis has been shown to highlight the impacts of these changes to temperature and precipitation on four Scottish lakes, with the data available for 5165 lakes in total. Potential evapotranspiration and a moisture metric (McCabe & Wolock 2002) are also calculated which are indicators of the impact of these changes on the hydrology of these standing freshwater systems. This shows increased PET across all sites, particularly during summer months, leading to sustained periods of water scarcity and deficit. This is likely to alter the function of these systems with resulting impacts on the ecological processes and function, species composition and conservation interest.

Finally, this chapter engaged with a climate change spatial risk assessment for Scotland highlighting those areas of the country projected to face the greatest changes to mean summer temperatures and precipitation. Using the 25km^2, 2050s, mid emissions, 50% probability model output over 200 lakes were found to be in the area of greatest change. Many of these lakes are already in challenging condition, and given that climate change impacts will likely exacerbate current pressures, management of these lakes will continue to be a major challenge. Further work is recommended on the sensitivity and vulnerability (see Chapter 4) of lake systems to change. Only by incorporating a wide range of internal and external factors, both direct and indirect, affecting the lake-landscape system can appropriate holistic management strategies and actions be formed.

Chapter 4: Sensitivity & Vulnerability: An index-based weighted relative climate change vulnerability analysis

4.1 Introduction

Vulnerability assessment frameworks using exposure, sensitivity and adaptive capacity have been applied to many species and ecosystems (Glick *et al.* 2011b; Dawson *et al.* 2011; Berry *et al.* 2013; McClure *et al.* 2013). A comparison of some of these found that the measures used to estimate these three components differ however (Berry *et al.* 2013). Generally, they considered exposure as the rate and magnitude of climate change in species ranges or habitats, either expressed by the extent of species ranges under climate changes (Rahel *et al.* 2008) or by the extent of the overlaps in species ranges between current and future climates (Thomas *et al.* 2012; Rout *et al.* 2013; Franklin *et al.* 2013). However, the distinctions between sensitivity and adaptive capacity are more ambiguous (Berry *et al.* 2013). The variations in measures used are partly due to differences in how the components are defined and the traits of target species, but also the purpose of the assessment and data availability. Berry *et al.* (2013) argue that climate change vulnerability assessment for conservation planning should include exposure, sensitivity and both adaptive capability and a related term: adaptation opportunity. However even for the charismatic megafauna investigated in the paper they struggled to find sufficient data to allow this to be truly viable. Given the paucity of ecological data for many species with any vulnerability assessment ensuring the quality of the data included will be important to ensure the legitimacy and utility of the study (Berry *et al.* 2013).

An index-based weighted analysis of vulnerability aims to organize a series of sub-analyses in a coherent structure that will shed light on distinct components of vulnerability, so that each can be evaluated individually, or in combination (Comer *et al.* 2012). This approach is related to a number of indexing approaches used for documenting at-risk status of biodiversity (Rowland *et al.* 2011), environmental impact assessment (Snover *et al.* 2013) and natural hazard risk management (Dana *et al.* 2012). Index-based weighted analyses have been widely utilised in ecological and socio-ecological studies in the recent past (Adger

2003, 2006; Vogel *et al.* 2007; Watson *et al.* 2011), particularly where concerns surrounding the complexity of impacts to increasingly threatened systems have led to a call for a prioritisation of data led management approaches using existing data rather than waiting for a perfect solution to appear in 'messy' systems (del Barrio *et al.* 2006; Charlesworth & Okereke 2010; Glick *et al.* 2011b). Cumulative or compounding effects are resolved by expert weighting of the model scoring structure (Polsky *et al.* 2007; Mumby *et al.* 2014). Furthermore, adaptive modelling schemes allow new data to be incorporated as it becomes available without rebuilding or recoding the entire model (Hinkel 2011).

Despite, or perhaps because of, the relative popularity of such approaches, and because the systems being investigated are so different, there is no single vulnerability analysis to suit all purposes. Instead, there are guidelines and best practises published (e.g. Glick *et al.* 2011) informing the use of the best possible data within a similar theoretical framework. Figure 4.1 illustrates eight such model examples. Each model is different not only in its construction, based on the scale of enquiry and data availability, but typically also uses different terminology with the attendant danger of misunderstanding and misrepresentation (Gallopín 2006; Smit & Wandel 2006; Hinkel 2011). The latest definitions for climate change vulnerability key terms from the IPCC AR5 WGII Glossary (Agard *et al.* 2014) are shown in Figure 4.2. However, because of the often interdisciplinary nature of climate change research these terms are still often confused or subject to multiple disciplinary definitions (Smit & Wandel 2006). This has led to confusion in the past and to the strong recommendation that clarity in the presentation of the language used in these models is key. This thesis continues to use the IPCC definitions and the ESVRA framework (see Chapter 1.5): Exposure refers to the external character, magnitude and rate of change of climate drivers. Sensitivity is a response term reflecting the intrinsic characteristics of a species or system. Vulnerability to climate change, as the term is used here, is the meeting of these two factors – sensitive systems or species likely to face extremes of climate changes will be most vulnerable (Glick *et al.* 2011a; b; Thornton *et al.* 2014). Additionally, it is important to clarify the related concepts of resilience and adaptive capacity as contributing factors to the sensitivity of the system.

Resilience is clearly an increasingly significant concept in socio-ecological studies (Folke 2006; Vogel *et al.* 2007; Morecroft *et al.* 2012), but one which has to date been under used as a structural part of vulnerability assessments (Glick *et al*. 2011). This deficiency is addressed in the current chapter using resilience as a key component of the vulnerability assessment (Figure 4.3). Following Gallopin (2006) here system sensitivity is expressed as the product of resilience (the capacity of the system to withstand changes whilst remaining in, or returning to, the known state) and adaptive capacity (the ability of the system to adapt to changing conditions). Resilience equates to the structural or physical characteristics of the lake, while adaptive capacity is linked to the quality of both the water body itself and the landscape in which it sits as fundamental in how whole systems can respond to change. More 'natural' systems are expected to have greater buffers to change and so ability to adapt over time meaning they are less vulnerable (Wilby *et al.* 2010; Rowan *et al.* 2012; Carpenter *et al.* 2014).

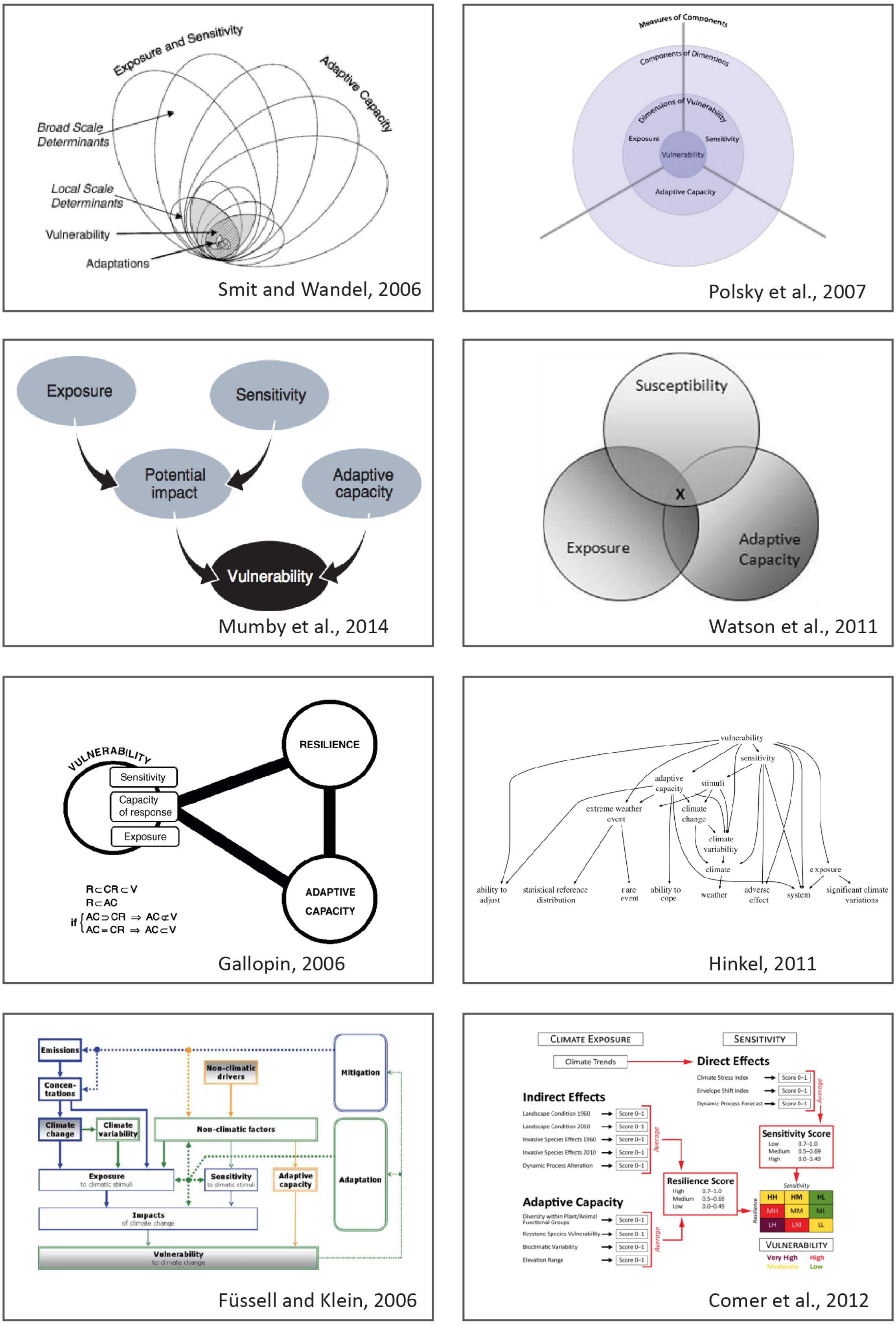


Figure 4.1 - An example of index based climate change vulnerability analysis models for ecological studies from published literature over the past 10 years. Each model combines elements of resilience, adaptive capacity, sensitivity and exposure though the terminology and structure differs depending on definition and focus.

Exposure
"The presence of people, livelihoods, species or ecosystems, environmental services and resources, infrastructure, or economic, social, or cultural assets in places that could be adversely affected."

Sensitivity
"The degree to which a system or species is affected, either adversely or beneficially, by climate variability or change. The effect may be direct (e.g., a change in crop yield in response to a change in the mean, range, or variability of temperature) or indirect (e.g., damages caused by an increase in the frequency of coastal flooding due to sea-level rise)."

Adaptive Capacity
"The ability of systems, institutions, humans, and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences."

Resilience
"The capacity of a social-ecological system to cope with a hazardous event or disturbance, responding or reorganizing in ways that maintain its essential function, identity, and structure, while also maintaining the capacity for adaptation, learning, and transformation."

Vulnerability
"The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts including sensitivity or susceptibility to harm and lack of capacity to cope and adapt."

Figure 4.2 - Key term definitions from IPCC AR5 WGII Glossary (2014)

Combining exposure data with elements of data relating to lake sensitivity to change enables both prioritisation of action at the national scale but also to investigate the site-specific links between the lake and its surrounding landscape (Soranno *et al.* 2010). The intention of the model is to recognise that different lakes, based on their structural form and landscape setting, will respond differently to change and hence will more be more or less vulnerable to climate change. Management actions can then be targeted both to the most vulnerable systems but also to the specific areas which are particularly sensitive, so as to increase resilience or adaptive capacity. It is important to note that this is exploring relative vulnerability within the lake system, not absolute vulnerability. It also cannot be considered a risk assessment, as it does not attempt to quantify uncertainty (Varis & Kuikka 1999). It is not attempting to say lakes or freshwaters broadly are more vulnerable than forests or uplands, for example, although in a study for SNH looking at all designated 'features' in Scotland, Brooker *et al.* (2013) which is built upon a similar framework, do reach this conclusion. Therefore, the creation of a vulnerability model for Scotland is key to determining conservation priorities for Scotland's threatened standing freshwaters.

Here the aim was to produce an index based weighted relative vulnerability analysis for Scotland's standing freshwater resource. Firstly, this involved an exploration of the concept of the sensitivity of Scotland's standing freshwaters where sensitivity is conceptualised as the convergence of resilience and adaptive capacity. Secondly, a transparent analytical procedure was developed and evaluated that can easily be used by conservation managers to investigate which of Scotland's lakes are most vulnerable to projected climate changes over the coming century.

4.2 Methods

4.2.1 Model Framework

The index-based analytical model used for this analysis is a unique construction. It builds upon a number similar approaches as outlined in Figure 4.1 (Füssel & Klein 2006; Gallopín 2006; Smit & Wandel 2006; Füssel 2007; Polsky *et al.* 2007; Watson *et al.* 2011; Hinkel 2011; Hofmann *et al.* 2011; Comer *et al.* 2012). In keeping with the majority of these vulnerability models, the calculation assumes a logical hierarchy of elements in producing a final vulnerability score, which can subsequently be ranked (Gallopín 2006; Watson *et al.* 2011). It incorporates exposure, sensitivity, adaptive capacity, resilience and vulnerability (as defined in Figure 4.2). It is informed by the data available for the standing water resource as produced in Chapters 2 and 3. Data from 17 sources is included in the model, which itself then calculates further 'scores' for each variable shown in Figure 4.3 below. It is likely that some variables will be auto-correlated (eg. altitude with temperature). Any effect on model outcomes is limited by combining and standardising the data and employing a weighting mechanism in the model calculations output in the relative scoring mechanism. The model was built in Microsoft Excel as a deliberate decision to maximise model transparency for the target audience of practitioners and policy.

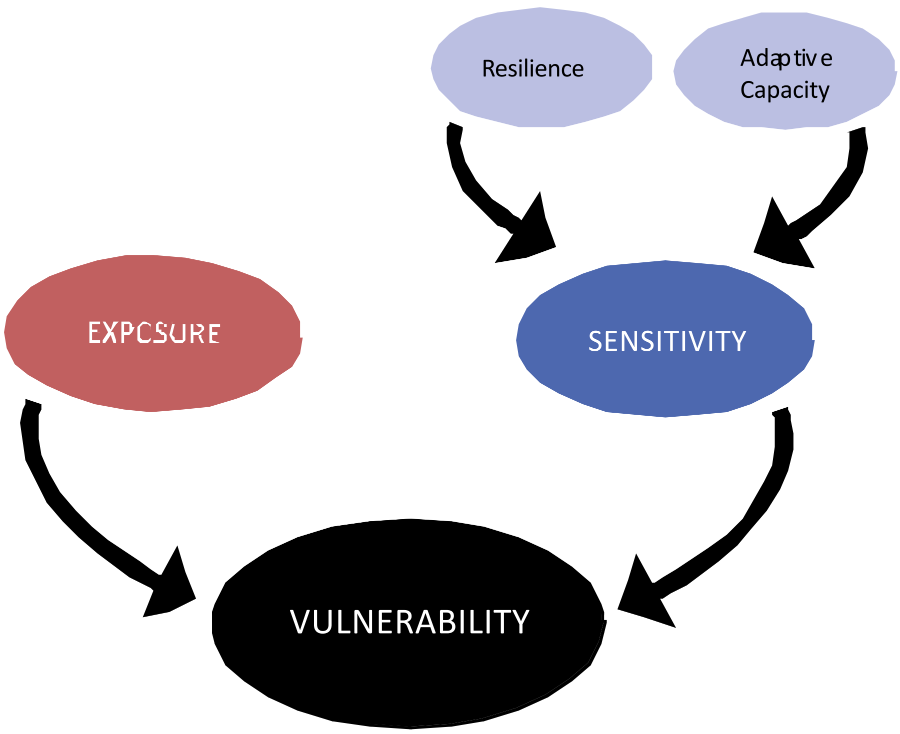


Figure 4.3 - Index based vulnerability assessment framework

4.2.2 Input variables

A wide range of data has been collated for this analysis, the majority of which has been explored in depth in the preceding chapters. These data have been allocated to the above data types as follows:

4.2.2.1 Exposure data

Exposure parameters were chosen for inclusion in the model based on quantitative evidence from the literature of a link between the environmental parameter of interest and ecological functions (Table 4.1). This led to the inclusion of eight climate model parameters, allowing full exploration of climate changes including projections of changes to annual trends, climate extremes and seasonal stresses. All data are derived from projected climate values for 2050s using the HadGEM2-ES climate model (Collins *et al.* 2011; Jones *et al.* 2011). HadGEM2-ES is the best choice for sensitivity and vulnerability assessment in the UK given its more recent earth system coupled data input, longer baseline and higher spatial resolution and global data set as discussed in Chapter 3.5.1. The model can be run with different weighting to these parameters (see 4.2.4 Calculating model scores). Values included in the analysis were:

AT: Change in Mean Annual Temperature (°C)

AP: Change in Mean Annual Precipitation (mm)

MTW: Change in Temperature of the Warmest Month (°C)

MTC: Change in Temperature of the Coldest Month (°C)

MPW: Change in Precipitation of the Wettest Month (mm)

MPD: Change in Precipitation of the Driest Month (mm)

SPMPE: Change in Summer PMPE moisture metric (mm)

WPMPE: Change in Winter PMPE moisture metric (mm)

4.2.2.2 Sensitivity data

As per the framework, system sensitivity was calculated based on data relating to both system resilience and adaptive capacity.

Resilience: Physical attributes of the lake system, including catchment area, are included as indicators of system resilience to change – that is the ability of the system to withstand changes whilst remaining in, or returning to, the known functional state. Categorical values for each of the following data sets were collated (see Chapter 3 for further details):

D: Mean Depth (m)

S: Size (ha)

Alk: Alkalinity (meq/l)

Alt: Altitude (m)

CTR: Catchment Size (ha)

Adaptive Capacity: Data relating to the current condition of the water body and linked landscape are included as indicators of the systems adaptive capacity – that is the ability of the system to adapt and respond to changing conditions where the original function or composition of the system may change. Data included in this analysis were discussed in Chapter 2:

SCM: Current Condition from SNH's site condition monitoring (SCM)

WFD: Overall Ecology Score from the Water Framework Directive (WFD) scoring system

LCI: Catchment Land Cover Intensity calculated per lake catchment from the LCM2007 dataset.

WS: Wildness Score calculated from SNH wildness mapping.

Table 4.1: The importance of each exposure parameter included in the model for ecological function of standing freshwater habitats.

Exposure Parameter	**Importance**	**Examples**
Mean Annual Precipitation	Precipitation is an essential contributor to standing freshwater quality and extent and changes in precipitation can impact organisms directly by changing habitat availability and indirectly through changes in nutrient load, visibility and oxygenation.	Fish (Carpenter et al. 1992); invertebrates (Bo et al. 2007)
Temperature of the Warmest Month	Many organisms live close to the limits of their thermal tolerance capacity. Surface water temperatures are directly related to air temperature. Increasing maximal temperatures may exceed species specific tolerance limits thus inducing mortality.	Invertebrates (Somero 2010); fish (Neuheimer et al 2011)
Temperature of the Coldest Month	Winter temperatures will dictate periods of freezing of water bodies. The duration and intensity of freezing is important in predicting species survival: too long/cold and species may not be able to tolerate/avoid being frozen or have problems obtaining food, too short/warm and hibernation and dormancy patterns may be disrupted. Changes to the timing and extent of snowmelt will also impact upon the hydrology of the system.	Mammals (Lane et al 2012); plants (Inouye 2000)
Precipitation of the Wettest Month	Increased precipitation can lead to extreme events such as flooding, which can cause direct changes to habitats and flushing of larvae or juveniles. Furthermore, increased flow into standing freshwater habitats could increase suspended solids and change nutrient levels. Suspended solids can reduce visibility, thus impacting feeding and breeding behaviour of aquatic organisms.	Fish (Ficke et al 2007); lake foodwebs (Donohue and Molinos (2009)
Precipitation of the Driest Month	Reduced precipitation will reduce the flushing of systems and increase residence times. This can lead to greater accumulation of phosphorus in sediments which, when released, can lead to harmful algal blooms. These blooms can block sunlight reaching the bottom of water bodies and thus reduce photosynthesis and oxygenation of water.	Fish (Elliott 2011); birds and mammals (Pybus et al 1986)
Summer PMPE Moisture Metric Winter PMPE Moisture Metric	Moisture Metrics combine the effects of temperature and precipitation as described above. These measures are taken at a seasonal level thus taking into account the effect on organisms of acclimatising to chronic changes in conditions rather than acute exposure to extreme events. The ability of organisms to cope with a change in environmental conditions is often reduced when exposed for longer periods.	Fish (Whitehead et al. 2011); invertebrates (Moya et al. 2015)

4.2.3 Data preparation

Data was assigned for every lake in Scotland (as previously defined, see Chapter 2) – 5,165 standing freshwaters in total. All of the analytical calculations used in this analysis can be followed in the associated spreadsheet.

The analytical procedure operates as follows. Firstly each of the 17 input data sets were combined into a single geodatabase in ArcGIS 10 (ESRI, 2011). This process links all the data sets together using a common water body identification number (WBID) and allows for data export to Microsoft Excel where each row of data relates to a single lake (unique WBID) and each column a different data set.

At this point categorical data (related to Resilience and Adaptive Capacity) was assigned a numerical value (Bierwagen *et al.* 2008; Lemieux & Scott 2011; Rosset *et al.* 2013) for example, mean depths (Deep, Shallow, Very Shallow) were assigned scores of 0-2 for high to low Resilience or Adaptive Capacity. See Table 4.2 for the full scoring breakdown.

For the model calculations to run it was necessary that all Exposure data were converted to give a positive absolute value. This assumes that the greater the magnitude of change, whether an increase or decrease, the greater the threat. Exposure data were scored where the data set mean plus one standard deviation (Z+1; the top 16% of values in a normally distributed data set) was scored as 2 (High Exposure), Z-1 was scored as 0 (Low Exposure) and all values in between scored as 1 (Mid Exposure) (Okkonen & Kløve 2010).

At this point each data set contains scores of 0, 1 or 2 as shown in Table 5.1. Each data set was then 'normalised' such that the data falls between 0 (the original minimum value) and 1 (the original maximum value). Data were normalised using the following formula:

$$x = \frac{(X - Xmin)}{(Xmax - Xmin)}$$

where Xmin and Xmax are the minimum and maximum values of this data variable respectively. This is an important process that standardises all data to a comparable form allowing the subsequent scoring analysis to take place (Brooker *et al.,* 2013). It would be necessary to recalculate if analysis at a different scale or focus (i.e. a subset of lakes in a specific region) was desired as it is specific to the maximum and minimum values of each particular analysis (Ippolito *et al.* 2010, Brooker *et al*., 2013).

4.2.4 Calculating model scores

Each element of the framework is calculated using three complementary methods. The first calculates each element using equally weighted arithmetic mean. The arithmetic mean is the mean or average with which most people are familiar, i.e. the sum of a set of values divided by the number of values.

Arithmetic Mean Equal weighting (ArM)

$$R(ArM) = \frac{D + S + Alk + Alt + CTR}{5}$$

$$AC(ArM) = \frac{SCM + WFD + LCI + WS}{4}$$

$$S(ArM) = \frac{R(ArM) + AC(ArM)}{2}$$

$$E(ArM) = \frac{AT + AP + MTW + MTC + MPW + MPD + SPMPE + WPMPE}{8}$$

$$V(ArM) = \frac{S(ArM) + E(ArM)}{2}$$

Where S = Sensitivity; R=Resilience; AC=Adaptive Capacity; E=Exposure and V=Vulnerability

The second is an equally weighted geometric mean (GeoM WEq). The geometric mean is "*n*th root of the product of *n* data" (Zar, 1996). It is useful for summarising sets of values where we are interested in their product rather than their sum (i.e. their multiplicative rather than net effects). This is useful where data may be related or expected to have competing and/or compounding effects. The geometric mean equal weighting is calculated using the same equations as shown above, but by calculating the arithmetic mean of the log(n+1) values of the normalised data (Mitchell 2004; ADAS 2010).

For the geometric mean calculations the scores are back-converted using antilog (final values) -1 to give vulnerability scorings with value between 0 and 1, which is more intuitive to interpret (0 = lowest vulnerability, 1 = greatest vulnerability).

The final scoring mechanism uses expert judgement to weight the data inputs (GeoM WEx) based on the two related assumptions. Firstly the weighting allows us to approach the issue of data quality and availability (Cook *et al.* 2012; Hameed *et al.* 2013). Secondly it allows an exploration of the relative significance or explanatory power of the data (Hagerman *et al.* 2010b; Martin *et al.* 2012; Dana *et al.* 2012). The weightings used here are shown in Table 4.2. These were chosen by discussion with supervisors and supporting staff at SNH and SEPA. Using expert weighting in this way is common (Anderegg *et al.* 2010; Donlan *et al.* 2010; Hubacek & Hiscock 2012) however it is not unproblematic as while it takes advantage of a great deal of experience, it is essentially a subjective measure. To counter this the model is constructed so that end users can adjust the scoring and weighting system and the results will automatically update based on the new inputs.

4.2.5 Output display

Here for each analysed score (E, S, V) values are recalculated using the Z1, Z-1 approach as described above to output a final score of 0, 1 or 2 following a 'traffic light' system such that Low (0) vulnerability = green, Mid (1)= amber, high (2) = red (Loehle 2011; Snover *et al.* 2013).

Vulnerability scores were exported from Microsoft Excel and imported to ArcGIS 10 (ESRI, 2011) to allow mapping of vulnerability scores. Data for specific lakes was also exported to Adobe Illustrator where a schematic was designed to highlight the contribution of each data input to the final ranking (see Figures 4.11-4.14). The display of data in such a visual manner can help practitioners and policy makers interpret data and lead to more informed management decisions (Zerger 2002; Zahran *et al.* 2008).

In the results section (Chapter 4.3) greatest attention is given to those lakes that are ranked High according to the expert weighted geometric mean results (GeoM WEx). The associated spreadsheet however allows the features to be sorted according to any of the inputs or calculated scores.

4.2.6 Model validation

Firstly, models with different weighting systems (i.e. ArM, GeoM WEq or GeoM WEx) were evaluated in terms of the presence of a significant correlation between the number of lakes classified within each vulnerability, exposure and sensitivity level for each weighting system. Secondly, correlations between the influence of the different metrics (grouped into exposure and sensitivity) and the final vulnerability score were assessed and fitted with a linear regression line. This was repeated for each model weighting system. Finally, different model weightings were visualised in terms of geographic distribution of vulnerability results using pin plots and nearest neighbour analyses. Nearest Neighbour' analysis calculates a matrix based on the average distance from each feature to its nearest neighbouring feature (del Barrio *et al.* 2006; Cook *et al.* 2007; Raven *et al.* 2010; Oliver *et al.* 2013; Hawes *et al.* 2013). This matrix is then stretch mapped in ArcGIS 10.2 (ESRI, 2011) to highlight clusters of data that give us a clear visual indication of the changed distribution.

Table 4.2 - Scoring and weighting mechanism for each model variable. Those values in darker shaded cells can be modified by end users.

EXPOSURE

VARIABLE	NORMALISED VALUE	SCORE	Weighting - Expert	N
AT	0.58	2		987
	0.28	1	0.05	3235
	0	0		943
AP	0.44	2		830
	0.13	1	0.05	3460
	0	0		875
MTW	0.62	2		889
	0.17	1	0.1	3488
	0	0		788
MTC	0.61	2		1059
	0.3	1	0.1	3499
	0	0		607
MPW	0.56	2		1012
	0.14	1	0.1	3320
	0	0		833
MPD	0.51	2		696
	0.11	1	0.1	4000
	0	0		469
SPMPE	0.46	2		1049
	0.25	1	0.25	3889
	0	0		227
WPMPE	0.53	2		1015
	0.08	1	0.25	3063
	0	0		1087

ADAPTIVE CAPACITY

VARIABLE	CATEGORY	SCORE	Weighting - Expert	N
SCM	Favourable	0		66
	Unfavourable Recovering Due to Management	1	0.2	3
	Unknown	1		5059
	Unfavourable	2		37
WFD	High	0		66
	Good	0	0.2	72
	Moderate	1		77
	Unknown	1		4839
	Poor	2		54
	Bad	2		57
CCI	High	2		776
	Mid	1	0.4	522
	Low	0		3867
WS	High	0		1010
	Mid	1	0.2	3363
	Low	2		792

RESILIENCE

VARIABLE	CATEGORY	SCORE	Weighting - Expert	N
CTR	D	0		64
	Sh	1	0.3	4876
	VSh	2		225
S	L	0		335
	S	1	0.2	1188
	VS	2		3642
Alk	LA	0		2407
	MA	0		1278
	HA	1	0.1	653
	Marl	2		54
	Brackish	2		36
	P	1		737
Alt	High	2		0
	Mid	0	0.3	0
	Low	1		0
CTR	Very Large	0	0.1	1
	Large	1		0
	Small	2		0

			Vulnerability WEq
		Exposure	1
Adaptive Capacity	**1**	**Sensitivity**	1
Resilience	**1**		

			Vulnerability WEx
		Exposure	1
Adaptive Capacity	**1**	**Sensitivity**	2
Resilience	**1**		

4.3 Results

4.3.1 Model Scores

The different scoring systems as described above provide us with different results as expected and are summarised in Table 4.3. In each case where expert weighting is considered the number of sites scored with High (2) is less than where no weighting takes place with fewer lakes classed as Highly Vulnerable to change using the weighted scoring method. This is to be expected as the GeoM WEx score double weights the site Sensitivity, which is a measure of the sites ability to respond, and as such mediates the exposure threat. The weighted result calculates 851 (16.5% of the full resource) as Highly Vulnerable, 3622 (70.1%) as Mid Vulnerability and 692 (13.4%) as Low Vulnerability.

Table 2.3 - Results of scoring systems ArM (Arithmetic mean); GeoM WEq (Geometric mean, no weighting); GeoM WEx (Geometric mean, weighted).

	Exposure			**Sensitivity**			**Vulnerability**		
	ArM	**GeoM WEq**	**GeoM WEx**	**ArM**	**GeoM WEq**	**GeoM WEx**	**ArM**	**GeoM WEq**	**GeoM WEx**
n HIGH	1081	1081	995	751	777	742	1051	988	851
n MID	3351	3351	3179	3701	3621	3685	3489	3530	3622
n LOW	733	733	991	713	767	738	625	647	692
	5165	*5165*	*5165*	*5165*	*5165*	*5165*	*5165*	*5165*	*5165*

As would be expected results for ArM and GeoM WEq are very similar and show close correlation (r^2 = 0.99; see Figure 4.4). The expert weighted analysis (GeoM WEx) also shows a correlation to both the ArM (r^2=0.78) and GeoM WEq (r^2=0.8) with differences here as anticipated showing that the scoring and weighting mechanism is working through the model.

Examining the influence of the different metrics on the final vulnerability score, illustrates that both exposure and sensitivity have a positive association with the final vulnerability score. This is normal and expected, as vulnerability is the summation of exposure and sensitivity. The relative influence of each Exposure and Sensitivity using the different scoring methods is shown in Figures 4.4 (ArM) and 4.5 (GeoM WEx). This illustrates the weighting effects with Exposure explaining for 75% of Vulnerability using the unweighted ArM and only 34% using the weighted GeoM WEx. There is no correlation between exposure and sensitivity using either scoring method.

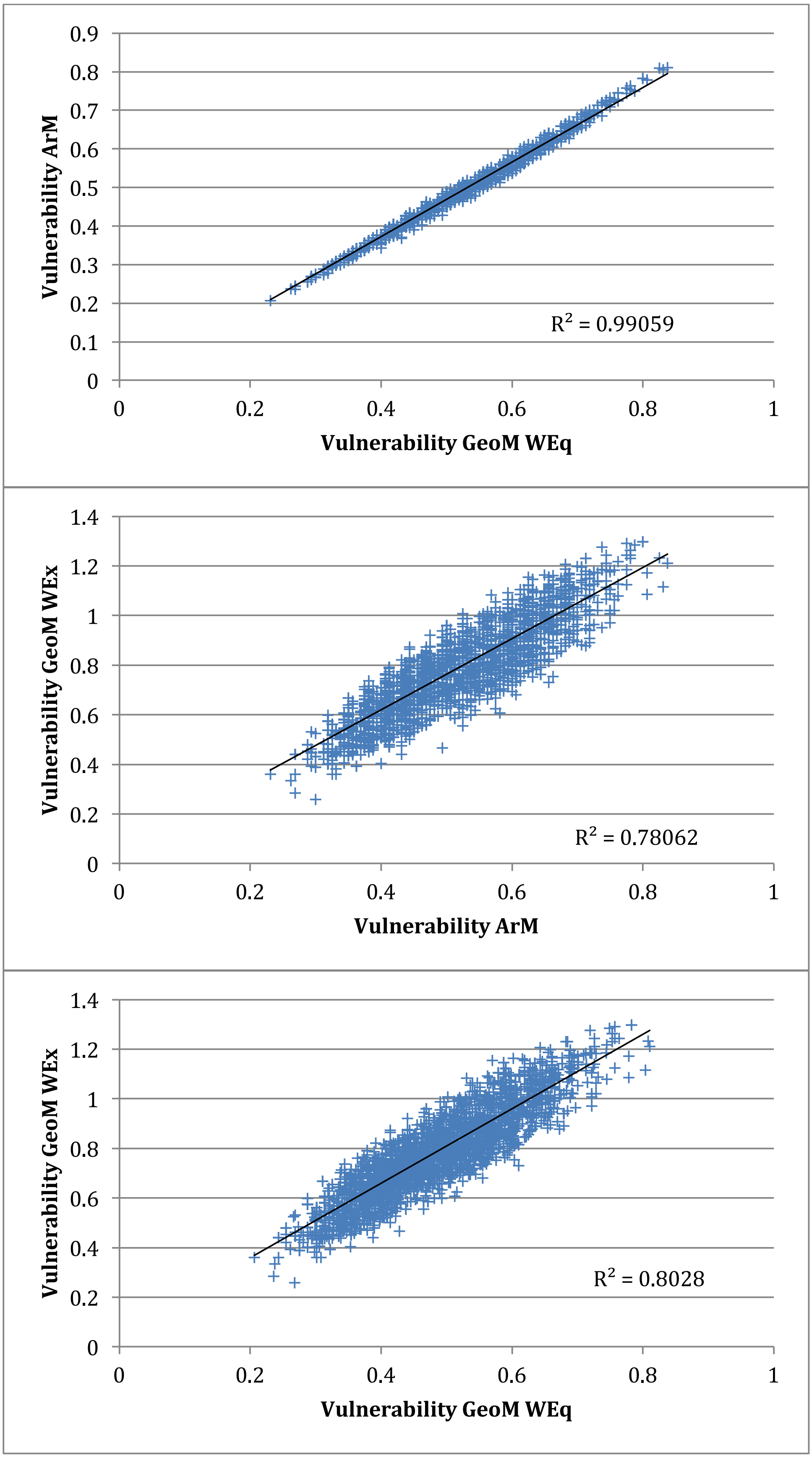


Figure 4.4 - Correlation between vulnerability scoring mechanisms

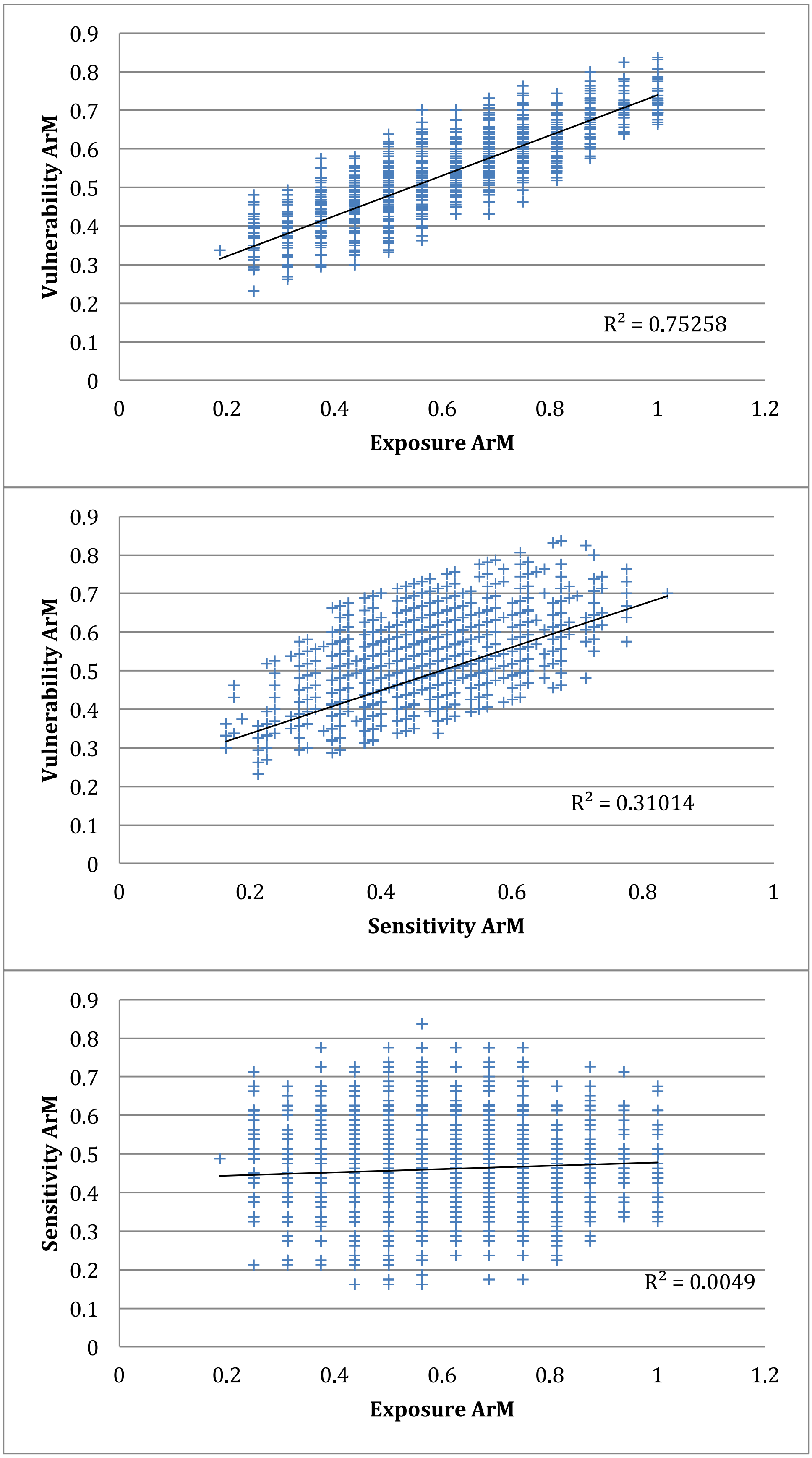


Figure 4.5 - Relationships between Sensitivity, Exposure and Vulnerability using the ArM scores

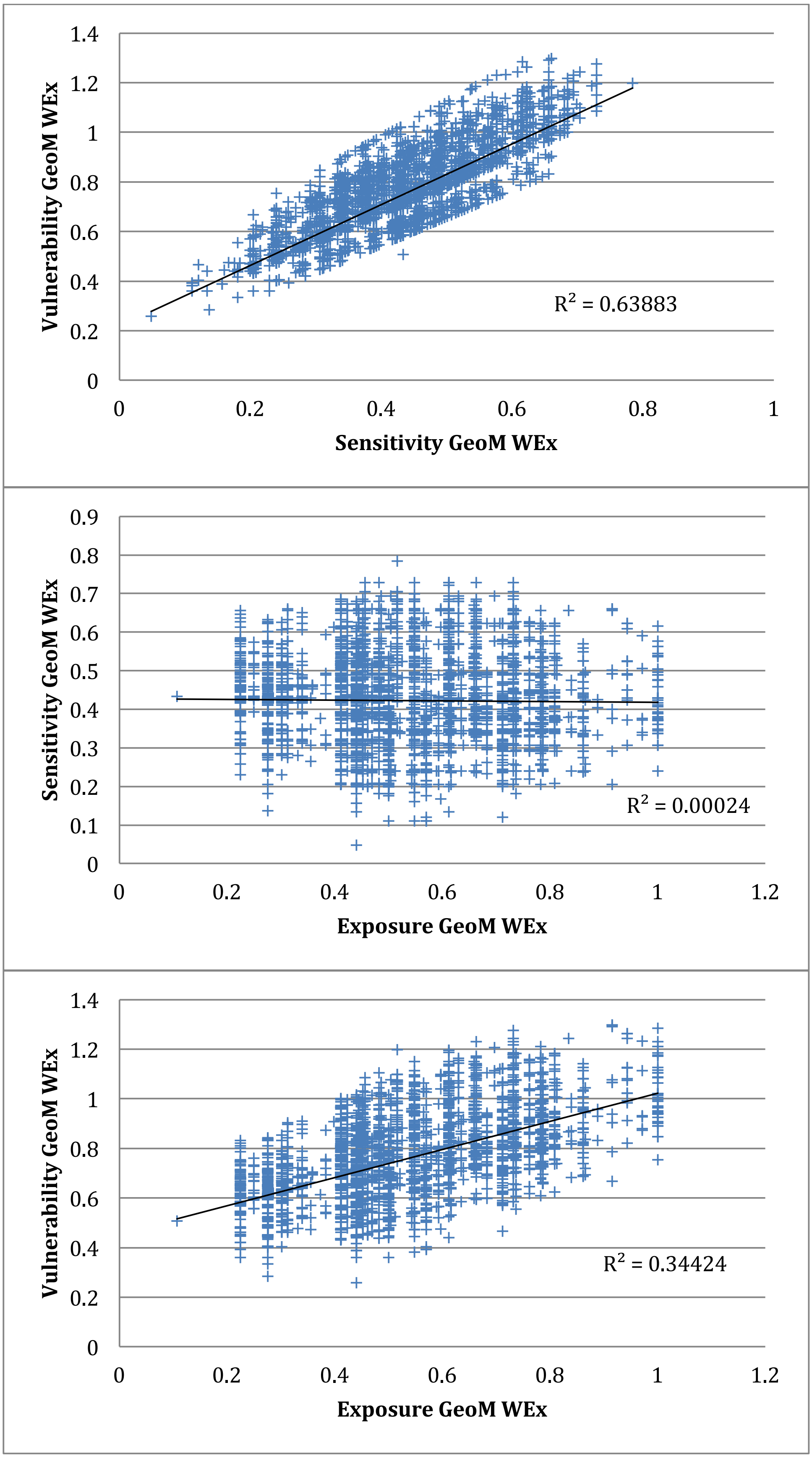


Figure 4.6 Relationships between Sensitivity, Exposure and Vulnerability using the weighted GeoM WEx scores.

4.3.2 Mapping vulnerability distribution

Given the South East – North West gradient in projected climate changes across Scotland (for example see Figure 3.13) it is expected that a mapped distribution for the unweighted scoring to follow a similar pattern. While this pattern should still hold true for the weighted calculations (GeoM WEx) it is likely that the weighted distribution (which double weights sensitivity against exposure) would show a more dispersed vulnerability distribution based on the specific landscape relationships of each lake. The pin plots of each GeoM WEq (Figure 4.7) and GeoM WEx (Figure 4.8) follow this pattern.

To further highlight this relationship, Figure 4.9 and Figure 4.10 show a 'Nearest Neighbour' analysis of these data. Using the unweighted data (GeoM WEq) the majority of data follows the anticipated climate projection pattern while the weighted data shows much greater variability across the country. Using the weighted data (GeoM WEx) shows a much more nuanced pattern across the country with lakes of low, mid and high vulnerability highlighted across the country. The visualisation of the results shows the model is working as expected and that differences based on the individual characteristics of the lakes within their landscapes are showing an effect on the model output.

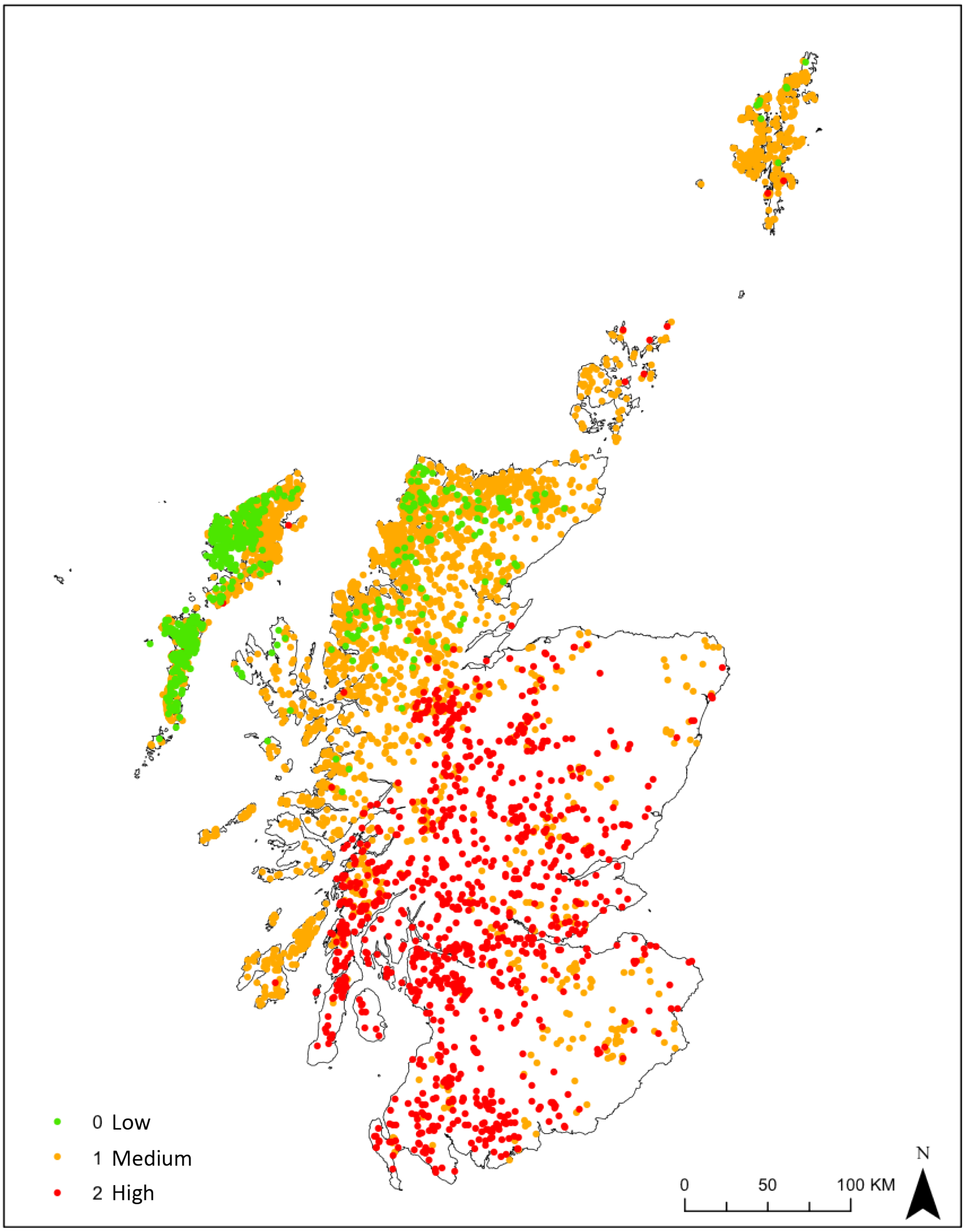


Figure 4.7 - Pin plot distribution of vulnerability results for 5165 lakes across Scotland using the unweighted arithmetic mean dataset (ArM). The distribution map shows strong similarity to a climate exposure map e.g. Figure 3.7

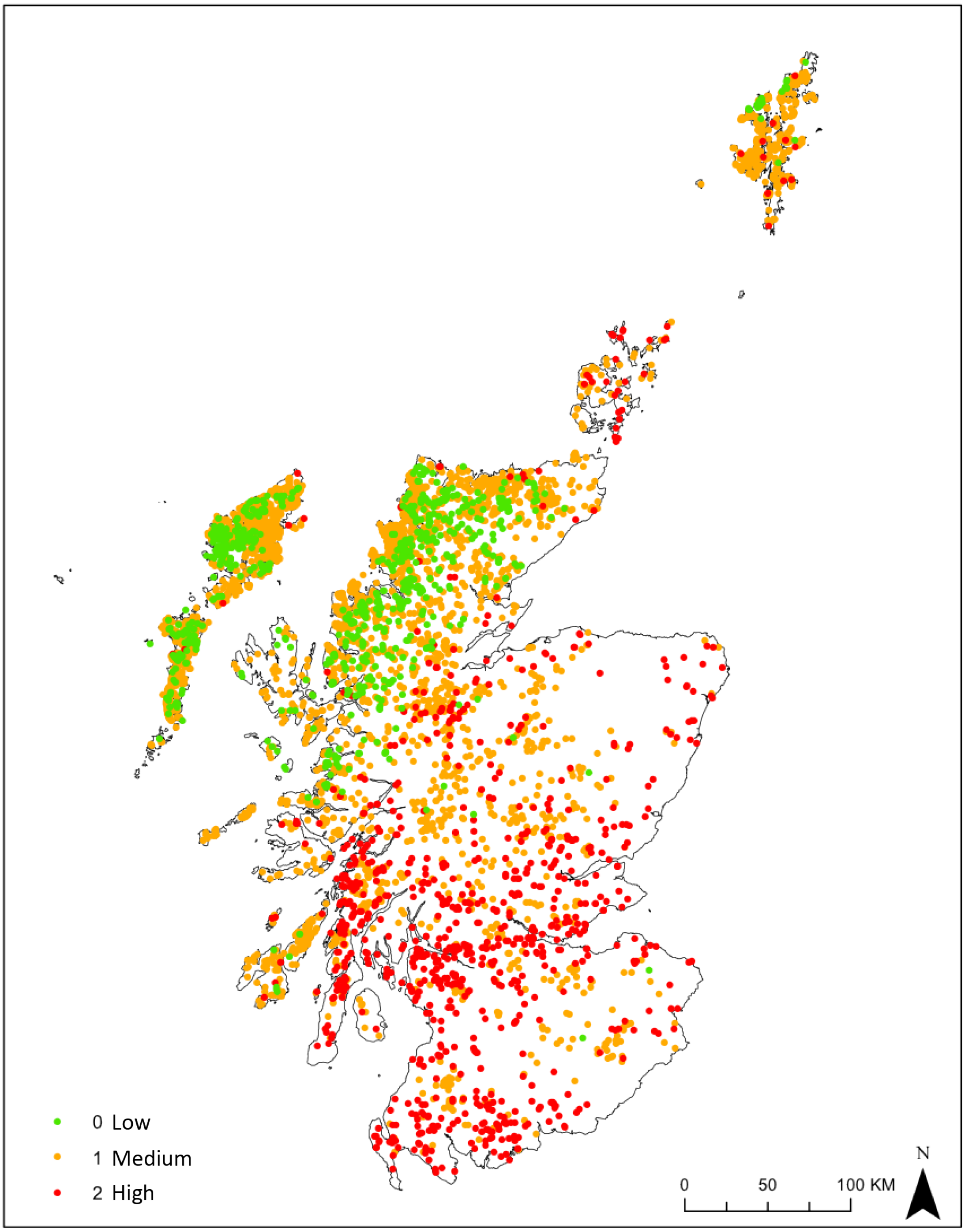


Figure 4.8 - Pin plot distribution of vulnerability results for 5165 lakes across Scotland using the GeoM WEx dataset. The distribution map shows a more widespread distribution of each score class due to the weighting of sensitivity data which is individual to each lake system.

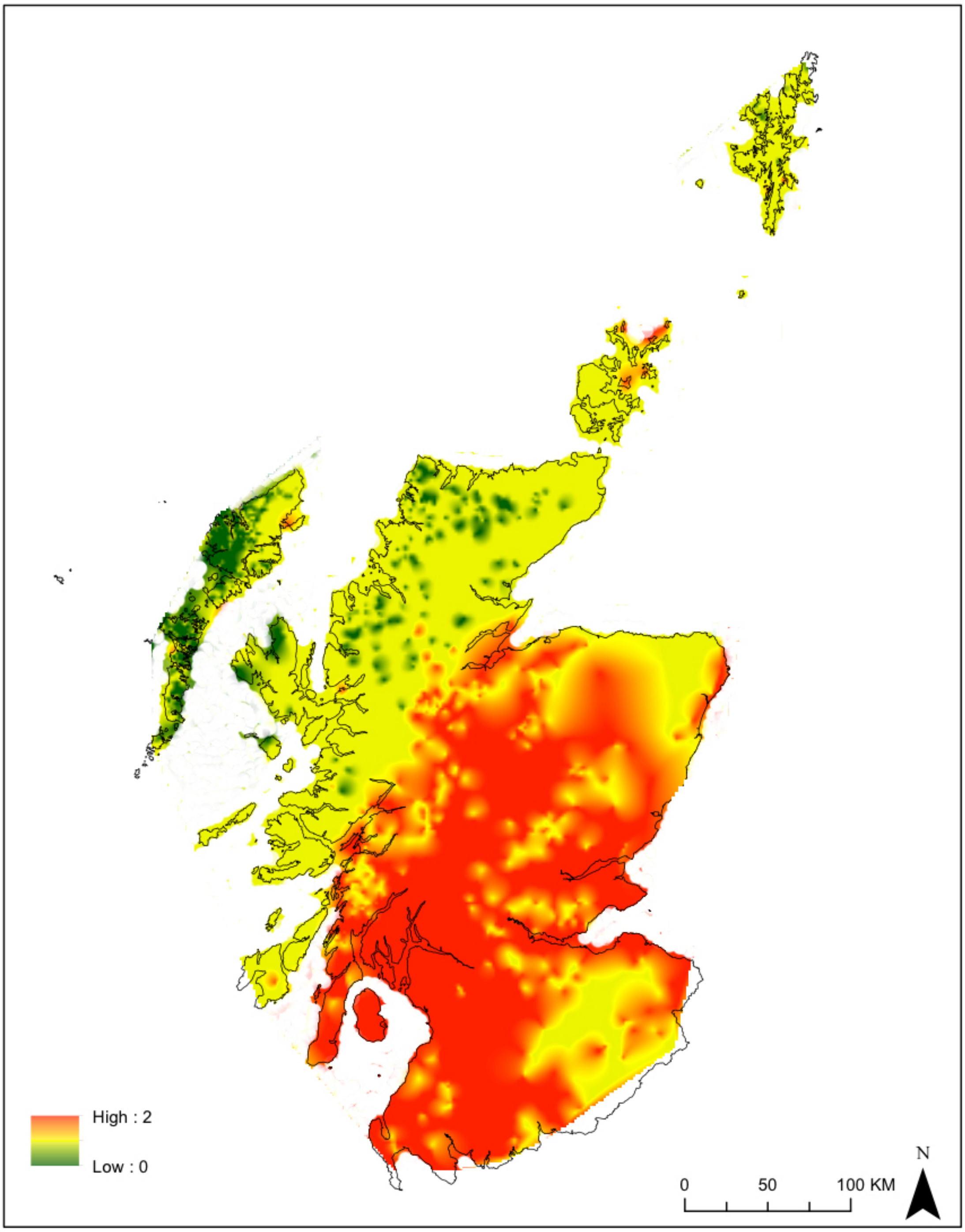


Figure 4.9 - Alternative form of data visualisation (nearest neighbour analysis) using the same unweighted ArM data as Figure 4.7.

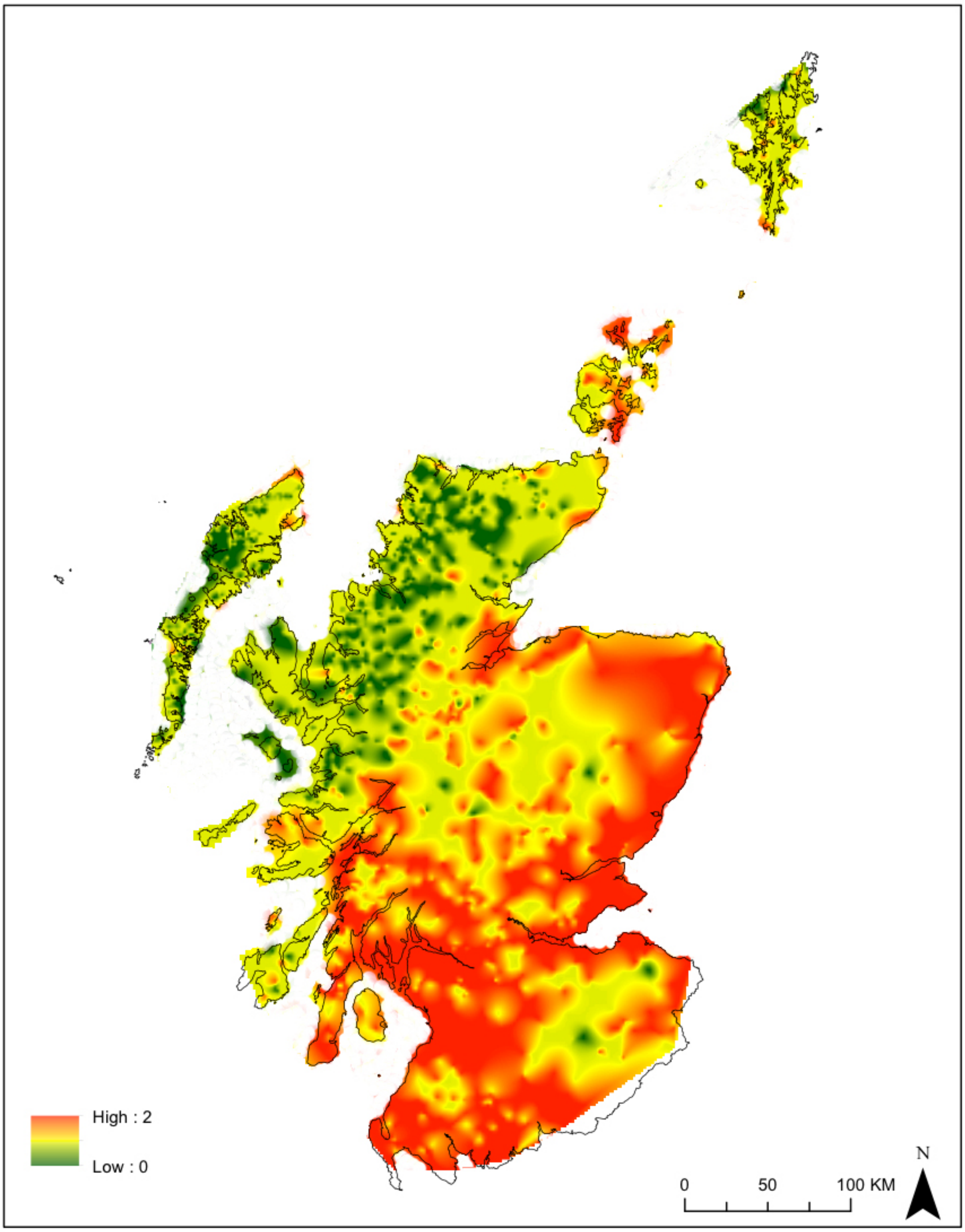


Figure 4.10 - Alternative form of data visualisation (nearest neighbour analysis) using the same weighted GeoM WEx data as Figure 4.8. This shows a more nuanced distribution of vulnerability across the country based on the specific sensitivities of lake habitats in Scotland.

4.3.3 Vulnerability Ranking

While this analysis is not intended to assess risk, it is still possible to rank lakes based on the vulnerability calculations. This may allow policy makers and practitioners to prioritise action. Table 4.4 shows the top 20 most vulnerable lakes based on each of the three scoring methods. The ArM and GeoM WEq rankings are very similar with 19 of the top 20 ArM lakes appearing in the GeoM WEq top 20. A number of these lakes (12) also appear in the GeoM WEx ranking but, as expected, this method shows more variability due to the weighting mechanisms. Black Loch (WBID 25738) for example appears at number 2 and 3 on the first two lists but slips to number 123 in the weighted scoring. The full ranking is available to search and sort on the associated spreadsheet.

Table 4.4 - 20 most vulnerable lakes as ranked by vulnerability scoring mechanism. The top 10 ArM lakes are coloured with all 10 appearing in the top 15 GeoM WEq results and 7 in the weighted GeoM WEx top 20.

ArM			GeoM WEq			GeoM WEx		
RANK	WBID	OSNAME	RANK	WBID	OSNAME	RANK	WBID	OSNAME
1	25887	unnamed	1	25887	unnamed	1	24940	unnamed
2	25738	Black Loch	2	25746	Coves Reservoir	2	24943	unnamed
3	25746	Coves Reservoir	3	25738	Black Loch	3	25778	unnamed
4	25214	Lochan Ghlas Laoigh	4	24940	unnamed	4	24842	Loch Dhu
5	25728	unnamed	5	24943	unnamed	5	26241	unnamed
6	24940	unnamed	6	25214	Lochan Ghlas Laoigh	6	24926	unnamed
7	24943	unnamed	7	25728	unnamed	7	25638	Loch Loskin
8	24842	Loch Dhu	8	26252	Greenan Loch	8	26252	Greenan Loch
9	26252	Greenan Loch	9	25778	unnamed	9	25939	Leperstone Reservoir
10	24926	unnamed	10	25939	Leperstone Reservoir	10	26535	Loch Libo
11	25638	Loch Loskin	11	26291	Loch Ascog	11	25746	Coves Reservoir
12	25453	unnamed	12	24926	unnamed	12	25453	unnamed
13	25778	unnamed	13	25638	Loch Loskin	13	27398	Martnaham Loch
14	25939	Leperstone Reservoir	14	25453	unnamed	14	27414	Belston Loch
15	26291	Loch Ascog	15	24842	Loch Dhu	15	27022	unnamed
16	25829	Whinhill Reservoir	16	27022	unnamed	16	25542	unnamed
17	27022	unnamed	17	27325	Knockruan Loch	17	25887	unnamed
18	27325	Knockruan Loch	18	25829	Whinhill Reservoir	18	28325	Loch Fern
19	24798	Loch Drunkie	19	25930	Gryfe Reservoirs	19	25907	Duddingston Loch
20	27234	Tangy Loch	20	27234	Tangy Loch	20	23610	Monk Myre

The full scoring breakdown for the top 20 GeoM WEx expert weighted scoring system is provided in Table 4.5, below. This table highlights the breadth of data that goes into the final vulnerability scores allowing a unique insight into the calculation process and the individual characteristics that contribute to each score.

Table 4.6 lists those lakes of current conservation priority (designated SSSIs) with 36 ranked as 'High' vulnerability using the GeoM WEx system. 18 are ranked as 'Low' vulnerability. Management resources should be targeted to those most vulnerable systems and this list should provide a useful starting point and focus for adaptation action in Scotland.

Table 4.5 Full scoring table for top 25 most vulnerable lakes in Scotland using the expert weighted (GeoM WEx) scoring system.

VEx RANK	WBID	NAME	D	A	ALK	ALT	LCR	SCM	WFD	WS	LCI	AT	AP	MT W	MTC	MPW	MP D	S PMPE	W PMPE	E WEx	AC WEx	R WEx	S WEx	V WEx
1	24940	unnamed	1	2	1	1	2	1	1	2	2	1	2	2	2	2	1	2	2	2	2	1	2	2
2	24943	unnamed	1	2	1	1	2	1	1	2	2	1	2	2	2	2	1	2	2	2	2	1	2	2
3	25778	unnamed	1	2	1	1	1	1	1	2	2	2	1	2	2	2	1	2	2	2	2	1	2	2
4	24842	Loch Dhu	1	2	0	1	0	1	1	2	2	2	2	2	2	2	2	2	2	2	2	1	2	2
5	26241	unnamed	2	2	1	1	1	1	1	2	2	2	1	2	2	1	1	2	1	2	2	2	2	2
6	24926	unnamed	1	2	0	1	1	1	1	2	2	2	2	2	2	2	1	2	2	2	2	1	2	2
7	25638	Loch Loskin	1	2	0	1	1	1	1	2	2	2	2	2	2	2	1	2	2	2	2	1	2	2
8	26252	Greenan Loch	1	1	1	1	1	1	1	2	2	2	2	2	2	2	1	2	2	2	2	1	2	2
9	25939	Leperstone Reservoir	1	2	1	1	1	1	1	2	2	2	1	2	2	2	2	2	1	2	2	1	2	2
10	26535	Loch Libo	1	2	1	1	1	2	1	2	2	2	1	2	2	1	1	2	1	2	2	1	2	2
11	25746	Coves Reservoir	1	2	2	1	2	1	1	1	2	2	1	2	2	2	2	2	2	2	2	2	2	2
12	25453	unnamed	1	2	0	1	1	1	1	2	1	2	2	2	2	2	2	2	2	2	2	1	2	2
13	27414	Belston Loch	2	2	0	1	1	1	1	2	2	2	1	2	2	1	1	2	1	2	2	2	2	2
14	27398	Martnaham Loch	2	1	1	1	1	2	1	2	2	2	1	2	2	0	1	2	1	2	2	2	2	2
15	27022	unnamed	1	2	2	1	2	1	1	2	2	2	1	2	2	1	1	2	1	2	2	2	2	2
16	25542	unnamed	1	2	1	1	1	1	1	2	2	2	1	2	2	2	1	2	1	2	2	1	2	2
17	25887	unnamed	1	2	1	0	2	1	1	2	2	2	2	2	2	2	2	2	2	2	2	1	2	2
18	28325	Loch Fern	2	2	0	1	1	1	1	2	2	2	0	2	2	1	1	2	1	2	2	2	2	2
19	25907	Duddingston Loch	2	2	1	1	2	2	1	2	2	2	0	2	2	0	1	1	1	1	2	2	2	2
20	23610	Monk Myre	2	2	1	1	1	1	1	2	2	2	1	2	2	1	1	1	1	1	2	2	2	2

Table 4.6 – Most vulnerable lakes of current conservation priority (SSSI designation) – 'High' Vulnerability GeoM WEx ranking No.=36) showing hydromorphological categories and management designation.

RANK	WBID	OSNAME	UK COUNTY	ALK	DEPTH	ALT	SIZE	SSSI DESIGNATION
10	26535	Loch Stiapahat	East Renfrewshire	HA	Sh	Low	VS	Eutrophic loch
13	27398	Loch Achnacloich	East Ayrshire	HA	VSh	Low	S	Mesotrophic loch
19	25907	Loch Spynie	City of Edinburgh	HA	VSh	Low	VS	Eutrophic loch
29	27234	Loch Oire	Argyll and Bute	MA	Sh	Low	S	Oligotrophic loch
64	24422	Loch Lundie	Fife	MA	VSh	Low	S	Mesotrophic loch
65	25613	Corby Loch	Stirling	MA	Sh	Low	VS	Mesotrophic loch
76	25477	Bishops' Loch	West Dunbartonshire	HA	Sh	Low	S	Eutrophic loch
171	25139	Loch of Aboyne	Fife	HA	Sh	Low	VS	Meso-eutropic loch
172	25303	Dun's Dish	Fife	HA	Sh	Low	VS	Eutrophic loch
206	21187	Loch of Kinnordy	Aberdeenshire	MA	VSh	Low	S	Mesotrophic loch
231	28111	Morton Lochs	Dumfries Galloway	HA	VSh	Low	L	Eutrophic loch
275	24840	Lindores Loch	Fife	HA	Sh	Low	VS	Mesotrophic loch
305	24894	Lochmill Loch	Fife	Marl	VSh	Low	S	Eutrophic loch
315	24439	Carriston Reservoir	Fife	HA	Sh	Low	VS	Mesotrophic loch
321	19262	Kilconquhar Loch	Highland	MA	Sh	Low	S	Eutrophic loch
396	26450	Loch Watston	Renfrewshire	MA	Sh	Low	L	Eutrophic loch
429	20454	Camilla Loch	City of Aberdeen	HA	VSh	Low	S	Mesotrophic loch
441	27149	unnamed	Scottish Borders	HA	Sh	Low	VS	Base-rich loch
463	23024	Caldarvan Loch	Angus	HA	Sh	Low	S	Eutrophic loch
466	27233	Carbeth Loch	Scottish Borders	HA	Sh	Low	S	Eutrophic loch
469	20466	Mugdock Loch	Aberdeenshire	HA	Sh	Low	VS	Mesotrophic loch
471	22679	Duddingston Loch	Angus	HA	Sh	Low	S	Eutrophic loch
490	25706	Possil Loch	Stirling	HA	Sh	Low	VS	Mesotrophic loch
515	26001	Coldingham Loch	City of Glasgow	HA	Sh	Low	VS	Mesotrophic loch
517	24933	Woodend Loch	Stirling	MA	Sh	Low	VS	Eutrophic loch
597	15332	Castle Semple Loch	Moray	HA	VSh	Low	S	Eutrophic loch
666	28200	Barr Loch	Dumfries Galloway	MA	Sh	Low	L	Oligotrophic loch
687	27510	Loch Libo	South Ayrshire	HA	Sh	Low	VS	Mesotrophic loch
693	14403	unnamed	Highland	HA	Sh	Low	VS	Eutrophic loch
717	26072	Yetholm Loch	Scottish Borders	HA	Sh	Low	VS	Eutrophic loch
743	26392	Tangy Loch	Renfrewshire	MA	VSh	Low	L	Eutrophic loch
751	28506	Martnaham Loch	Dumfries Galloway	MA	VSh	Low	L	Oligotrophic loch
774	24070	Drumore Loch	Fife	HA	Sh	Low	VS	Loch trophic range
775	26167	Milton Loch	North Lanarkshire	Brackish	VSh	Low	S	Base-rich loch
798	2272	Woodhall Loch	Na h-Eileanan an Iar	HA	Sh	Low	VS	Eutrophic loch
810	16142	Mochrum Loch	Moray	HA	Sh	Low	VS	Mesotrophic loch

Table 4.7 – Least vulnerable lakes of current conservation priority (SSSI designation) – 'Low' Vulnerability GeoM WEx ranking No.=18) showing hydromorphological categories and management designation.

RANK	WBID	OSNAME	UK COUNTY	ALK	DEPTH	ALT	SIZE	SSSI DESIGNATION
5005	1271	Loch of Girlsta	Shetland Islands	LA	Sh	Low	L	Arctic Charr
5073	5350	Loch Stack	Highland	LA	Sh	Low	L	Oligotrophic loch
4770	5700	Loch Rumsdale	Highland	P	Sh	Low	VS	Oligotrophic loch
4731	6176	Loch Lacsabhat Iarach	Na h-Eileanan an Iar	P	Sh	Low	S	Oligotrophic loch
4733	6375	Loch Laxavat Ard	Na h-Eileanan an Iar	HA	Sh	Low	S	Oligotrophic loch
5156	8751	Loch Assynt	Highland	MA	D	Low	L	Eutrophic loch
4931	10934	Cam Loch	Highland	MA	Sh	Low	L	Oligotrophic loch
4933	11385	Loch Urigill	Highland	MA	Sh	Low	L	Oligo-Mesotrophic
5157	14057	Loch Maree	Highland	LA	D	Low	L	Oligotrophic loch
5069	14627	Loch Fada	Na h-Eileanan an Iar	MA	Sh	Low	L	Oligotrophic loch
4699	17239	Loch Lundie	Highland	MA	Sh	Mid	L	Mesotrophic loch
5162	18682	Loch Druidibeag	Na h-Eileanan an Iar	MA	Sh	Low	L	Machair loch
4597	19540	Loch Ruthven	Highland	MA	Sh	Mid	L	Mesotrophic loch
4802	20860	Loch Insh	Highland	LA	Sh	Mid	L	Mesotrophic loch
5121	21466	Loch Morar	Highland	MA	D	Low	L	Oligotrophic loch
4954	21925	Loch Shiel	Highland	MA	D	Low	L	Oligotrophic loch
4626	22782	Loch Rannoch	Perth and Kinross	LA	D	Mid	L	Oligotrophic loch
5037	27309	St Mary's Loch	Scottish Borders	MA	D	Mid	L	Oligo-Mesotrophic

4.3.4 Output Display

Figures 4.11 – 4.14 show the results for four individual lakes. These examples show the scoring system working as designed to highlight the individual characteristics of each lake and the links with the landscape scale data. These lakes were originally selected to show the climate change impact on lakes across the country and on lakes with different hydromorphological characteristics (see Chapter 3.3.2; Table 3.1) and as such the scoring mechanism should reflect these differing characteristics. This is most clearly demonstrated in the difference between Loch Maree (Figure 4.13) and Loch of Kinnordy (Figure 4.14). Loch Maree is a large, deep lake in the relatively unpopulated North West Highland which is projected to face less extreme climate changes than further South (see Figure 3.7). A lake with these characteristics is believed to have high resilience and adaptive capacity and thus have a low sensitivity score and low vulnerability. Indeed Loch Maree ranks in the lowest 1% of lakes (5142 / 5165) in Scotland. Loch of Kinnordy, on the other hand is a very small eutrophic lake in more populated region of Angus scores with higher projected climate impacts, greater sensitivity and thus much higher vulnerability. It ranks in the top 10% (463 / 5165) of vulnerable lakes.

Displaying the data in this way allows us to see the clear links between model input variables and the calculation of vulnerability scores. This transparency should both enhance the understanding of the modelling process, and thus trust in the outputs, while also allowing a quick visualisation of areas where management actions could be targeted to improve the specific areas of system resilience and adaptive capacity.

WBID	23465			
SCORING SYSTEM	EXPOSURE	SENSITIVITY	VULNERABILITY	RANKING
ArM	0.88	0.45	0.66	297
GeoM WEq	0.86	0.40	0.62	379
GeoM WEx	0.81	0.41	0.93	697

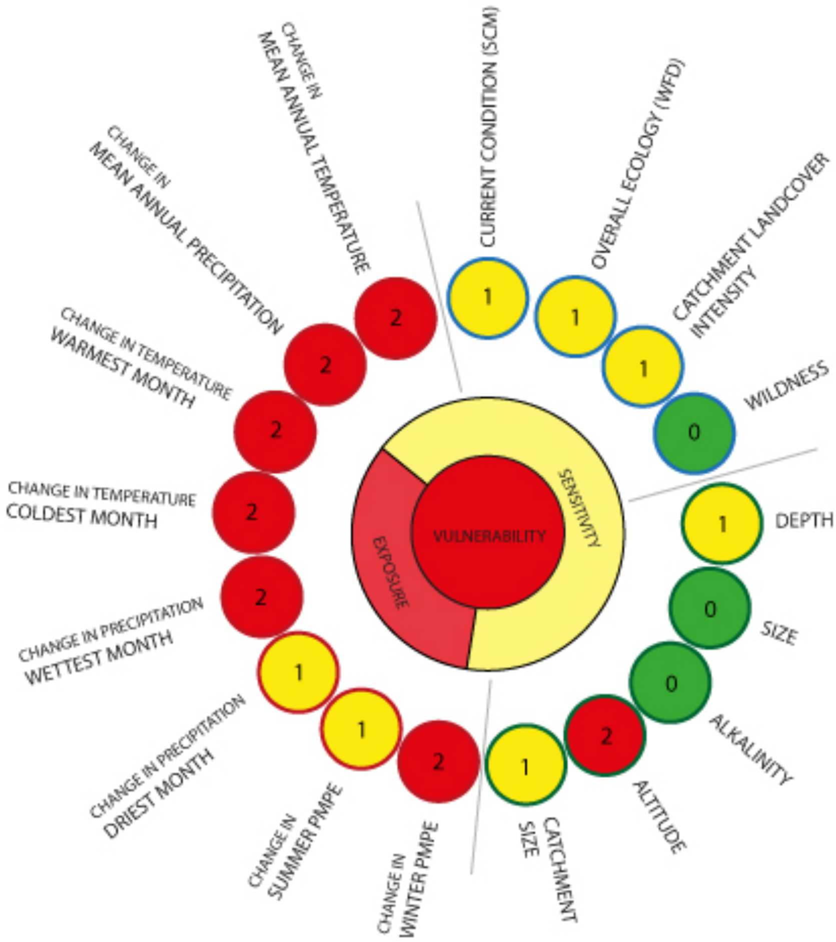


Figure 4.11 - Example of vulnerability data display for Loch an Daimh, a large, high altitude, shallow lake in Perth and Kinross.

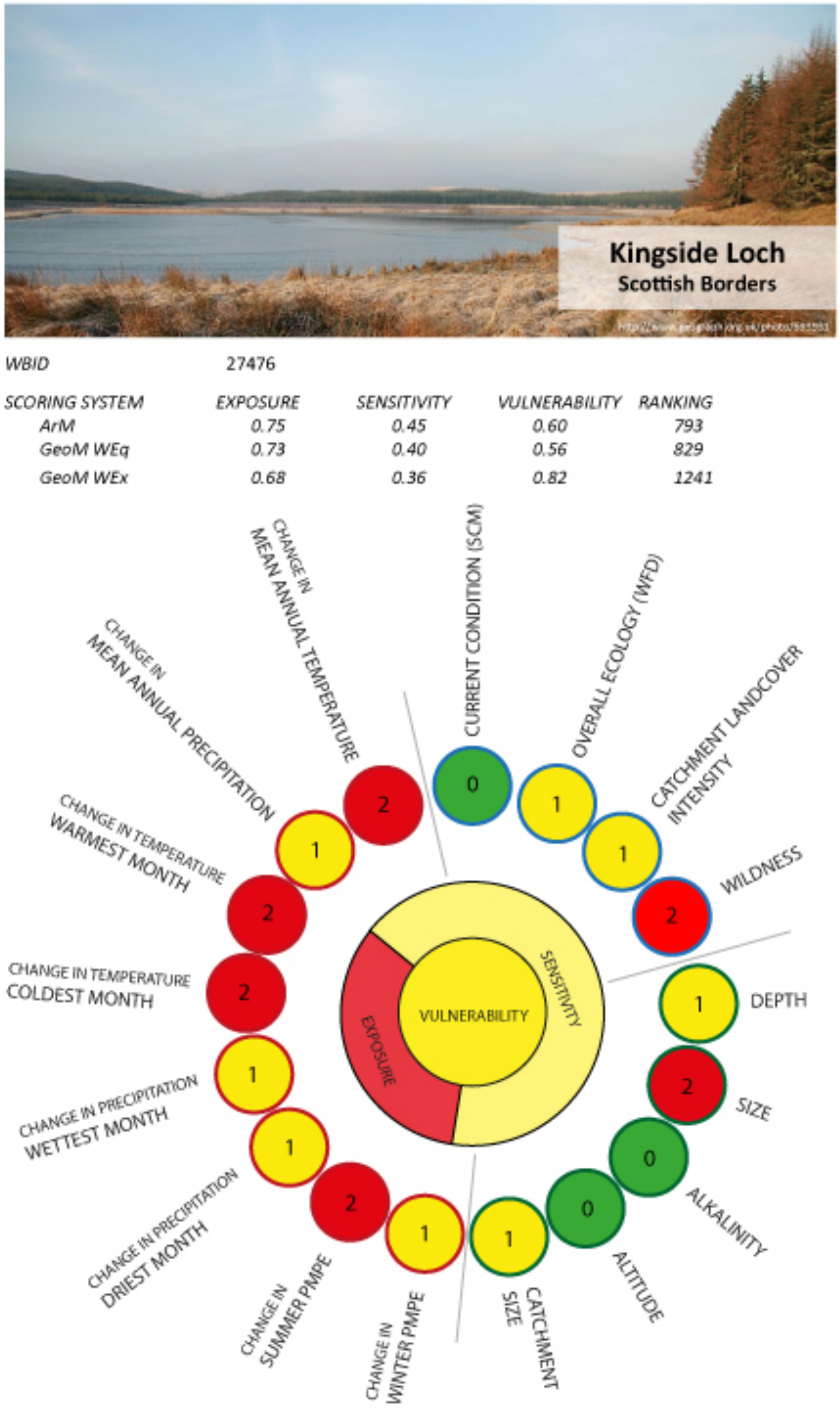


Figure 4.12 - Example of vulnerability data display for Kingside Loch, a very small, shallow lake in the Scottish Borders.

WBID 14057

SCORING SYSTEM	EXPOSURE	SENSITIVITY	VULNERABILITY	RANKING
ArM	0.44	0.16	0.30	5143
GeoM WEq	0.43	0.14	0.28	5142
GeoM WEx	0.44	0.16	0.39	5157

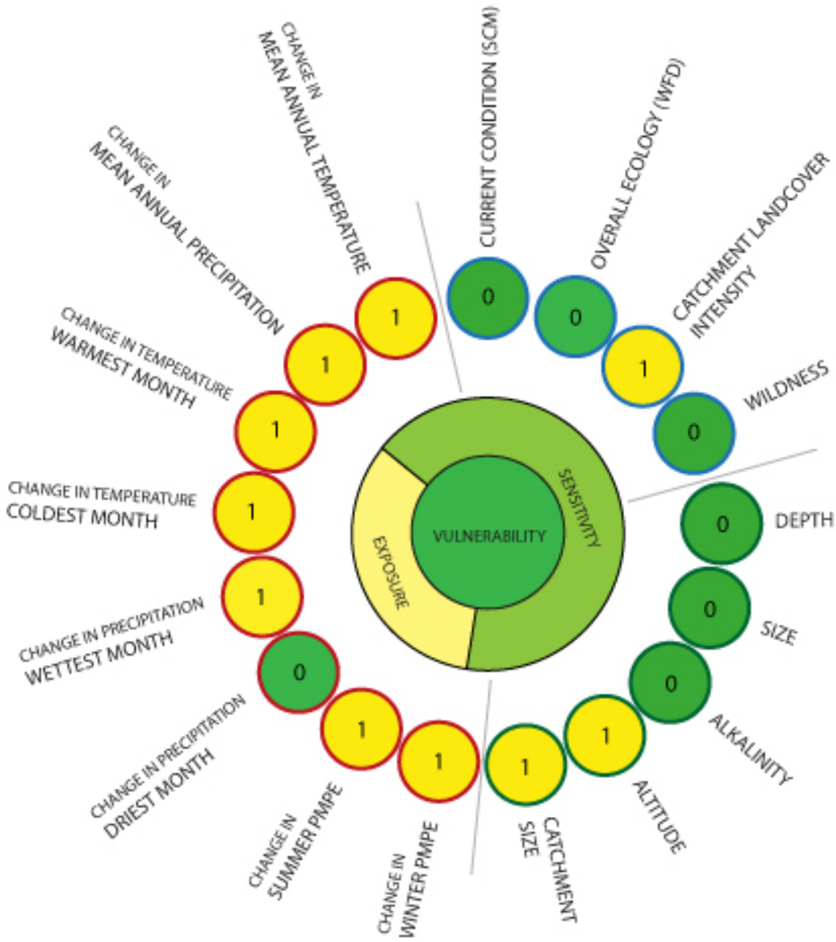


Figure 4.13 - Example of vulnerability data display for Loch Maree, a large deep lake in the North West Highlands.

WBID 23024

SCORING SYSTEM	EXPOSURE	SENSITIVITY	VULNERABILITY	RANKING
ArM	0.69	0.68	0.68	199
GeoM WEq	0.67	0.66	0.66	143
GeoM WEx	0.57	0.55	0.99	463

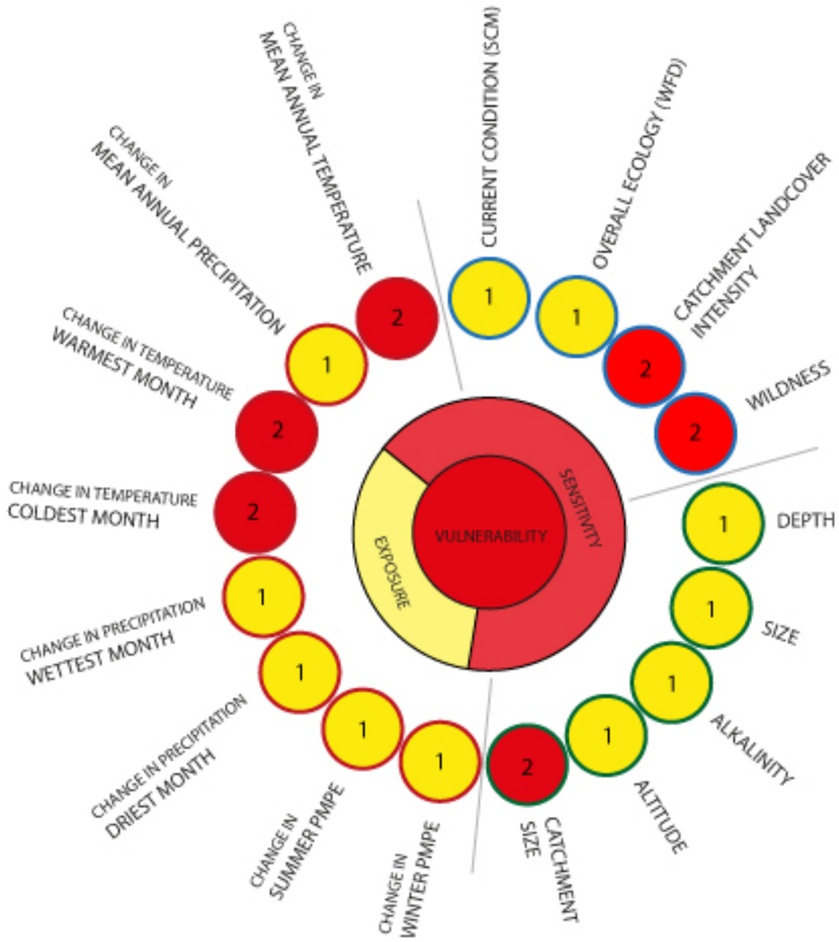


Figure 4.14 - Example of vulnerability data display for Loch of Kinnordy, a very small shallow lake in Angus.

4.4 Discussion

The results presented here give a strong indication that the proposed vulnerability framework and model is working as expected. This is a major achievement, collating 17 data sets, over 3 million data points, and creating a model which fits within a clear and considered theoretical framework – the elements of which are clearly defined and relevant to a socio-ecological study at this scale (Folke *et al.* 2010; Nichols *et al.* 2011; Raymond *et al.* 2013). The model fuses global climate change data with regional and site-specific datasets and provides an analysis which should provide policy makers and practitioners with a strong, transparent and responsive set of results to help focus management action at multiple scales (Cross *et al.* 2012a; Ausden 2014; Moss 2014).

4.4.1 Input data & model mechanism

The elements of the climate model used have been specifically chosen to provide a comprehensive understanding of system exposure. As discussed in Chapter 3, HadGEM2-ES climate models give preferable outputs to UKCP09 or other available data sets. 2050s projected climate data has been the focus throughout this study and it is unlikely that 2080s data would change the scoring or distribution significantly because the climate scores are based on the relative scale not the absolute value (Brooker et al., 2013).

Annual patterns are not the only issues which will impact on the natural environment, in fact it is likely that extremes and seasonal changes will be extremely important for both hydrology and ecology of freshwater systems (Johnson *et al.* 2009; Carvalho *et al.* 2012; Warfe *et al.* 2013). To this end, modelled data related directly to annual change, as well as data relating to changes to climate extremes and seasonality are incorporated in the exposure analysis using recognised global climate models to inform our understanding of resource exposure to all aspects of climate change (Munang *et al.* 2010; Snover *et al.* 2013). This wide ranging analysis gives a much fuller exploration of the climate change exposure threat to standing freshwater systems in Scotland than using projected annual trends alone.

The most complex part of the model framework is the detail of system sensitivity when dealing in particular with such a large and wide ranging resource (Comer *et al.* 2012).

Sensitivity, adaptive capacity and resilience are much more resource specific and reaching conclusions on the relative merits of one data set over another, or indeed having access to the most relevant data is a challenge (Evans *et al.* 2006; Soranno *et al.* 2010; Doswald *et al.* 2014) The approach adopted here concentrates on assembling the model making the best use of the data available. Much analysis is based on expert judgement or literature review however, as it is unknown to what extent system features are linked and do not have empirical data relevant to the national scale, nor data focussed on system functionality (Cadotte 2011; Cadotte *et al.* 2011; Strayer & Hillebrand 2012; Steudel *et al.* 2012). The model construction allows end users to modify the scoring and weighting structure, which should alleviate individual concerns whilst allowing the use of the best data available at this scale.

For simplicity of display and communication the calculated vulnerability scores are assigned to a High/Mid/Low score. Here this assignation is made based on the Z scores, as discussed, which is a reasonable and statistically relevant way of categorising a large dataset. Elsewhere (e.g. Brooker *et al.* 2013) this categorisation is done by trial and error to allow only the top 50/75/100 scores to be scored 'High'. The approach advanced here is considered to be more robust and gives a truer, though still calculated, analysis of the vulnerability to climate change across the whole resource while the ranking of vulnerability scores still allows the 'top 100' (or similar) lists to be produced if required.

The systematic structuring of the vulnerability assessment makes the addition of new data sets relatively straightforward (Polsky *et al.* 2007; Rowland *et al.* 2011). The scoring and weighting structure also allows us to incorporate measures based on expert opinion as well as those based on empirical study (Ippolito *et al.* 2010; Hinkel 2011) which could be useful in the future to reduce some of the current limitations of the vulnerability assessment method.

4.4.2 Limitations of vulnerability assessment approach

While the results presented here are clear, there are arguably limitations to the utility of such a vulnerability assessment approach (Charlesworth & Okereke 2010; Hofmann *et al.*

2011). To start, the assessment makes no attempt to assess uncertainty and as such cannot be considered, and is not intended to be considered, a risk assessment. Other analysis methods which do attempt to include probabilistic uncertainty – such as Bayesian Belief Networks (Varis & Kuikka 1999; Henriksen & Barlebo 2008; Dlamini 2010; Aalders *et al.* 2011) were considered for this assessment but were dismissed as too complex to be useful for end users (Cook *et al.* 2007, 2013; Martin *et al.* 2012) after discussion with representatives of SNH and SEPA.

Secondly, an assessment of this type presupposes that all climate change impacts will be negative whereas there may also be positive impacts across the resource (Lindenmayer *et al.* 2010; Falloon & Betts 2010). This is because the data used herein which relates to the adaptive capacity and resilience of the system is based upon current status, rather than on a modelled future condition. To assess which elements of the system might benefit from climate change we would need extensive modelling of, for example, projections to land use change, which could then be assessed against current data to inform a change in Land Cover Intensity metric which could be either positive or negative. While work of this kind has already been done (Rounsevell & Reay 2009; Falloon & Betts 2010; Trnka *et al.* 2011) the data were not available at the necessary scale for this study though it could be a useful future addition. Attempting to model changes in each of the adaptive capacity indicators is well beyond the scope of this analysis but could be extremely useful in allowing us to approach the concept of adaptive capacity increase or deficit (Smit & Wandel 2006).

Fundamentally, the strength of the model relies on the quality and relevance of the data available, and the data available for habitats as opposed to species is a further potential weakness. There are two main areas in which the current available data are lacking, or where the vulnerability assessment could be strengthened. The first would be to include a measure of ecological connectivity as it is believed that better connected systems have higher adaptive capacity to change (Hansson & Angelstam 1991; Watts *et al.* 2010; Van Looy *et al.* 2013). Connectivity matrix are complex to produce for habitats like lakes which are static yet home to multiple movable species with both upstream and downstream connectivity (Weatherhead & Howden 2009; Mooij *et al.* 2010; Hijmans & Elith 2011). While water has become more integrated and acknowledged in studies of landscape ecology (Wiens 2002; Turner 2005; Soranno *et al.* 2010; Monk *et al.* 2013) there are no studies which attempt to do this and this could be an interesting area for further research. Secondly, it would be ideal to include a measure of functional complexity or species diversity within the model. Greater diversity is expected to give a habitat greater resilience to change as multiple species may fill functional niches (Cadotte 2011; Buisson *et al.* 2013; Turnbull *et al.* 2013; Tomimatsu *et al.* 2013). Habitat vulnerability is complex because of the very many biotic and abiotic components which combine to produce a functioning system (Whitman *et al.* 2013). Where it is relatively simple to gain a deep understanding of the life cycle, range, trophic level interactions and requirements of a single species, all elements which can be modelled using species distribution model, this is simply not possible for vastly more complex habitat systems like standing freshwaters.

4.4.3 Model Potential and Expected Use

While there are undoubtedly limitations to this approach as described above, the general output from the model provides a huge potential to focus management of the Scottish standing freshwater resource in the face of climate changes over the coming century. As well as site specific or national scale results, as presented here, it is possible to use simple GIS techniques to map the results by catchment or local authority region. This could be achieved either using results as they stand (so regional results placed within Scottish context) or by recalibrating the data sets to give within region fully relative results.

The simplicity of the framework, particularly the framing of resilience as a key element of the model, could also easily be used for other habitats and species of conservation interest globally. The exposure data presented here is from a global data set and could be used at a range of scales from site specific to national or cross-boundary studies (Tabor & Williams 2010). The particular data used to calculate resilience and adaptive capacity would need to be given some thought based on the particular object of study, but is undoubtedly possible no matter what the object of interest (Hofmann *et al.* 2011; McClure *et al.* 2013). Explicitly linking resilience to physical or structural characteristics of a habitat, and adaptive capacity to the current quality, health or ‘naturalness’ of the system is a clear, strong and replicable basis for the addition of these characteristics to the model.

In the first instance, conservation management should focus on the most vulnerable systems (Hulme 2005; Dow *et al.* 2007; Clarke 2009; Doswald *et al.* 2014; Khamis *et al.* 2014). The model presented here allows identification of the most vulnerable standing freshwater systems in Scotland, thus focussing management strategies. Furthermore, it will allow management actions targeted to increase the resilience and adaptive capacity of the system, providing an invaluable resource for policy makers and practitioners.

4.5 Summary

Vulnerability assessments have become increasingly popular in socio-ecological studies over the past decade as they allow the systematic combination of both empirical and expert based data sources to deal with complex systems. This chapter aimed to explore the concepts of vulnerability and sensitivity, and the closely related constructions of resilience and adaptive capacity. The vulnerability framework created for this study is based upon clear understandings of complex terminology and deliberately attempts to place resilience as a key part of the model which has to date been missing from similar studies.

5165 lake habitats were analysed in the most comprehensive vulnerability assessment known to have been undertaken for this national resource. 17 data sets were compiled within the vulnerability framework, including 8 related to exposure to climate change (data representing projected annual change, extremes and seasonality); 9 related to system sensitivity containing 5 data sets related to system resilience (structural components) and 4 related to system adaptive capacity (quality and naturalness).

The expert weighted scoring mechanism highlights 851 of Scotland's standing freshwaters as being highly vulnerable to projected climate changes. This represents 16.5% of the entire resource and is geographically spread across the country. Model scoring mechanisms have been shown to be working and investigated in depth allowing the clear conclusion that the weighted expert geometric mean scoring system gives a strong output which policy makers and practitioners can have confidence in. Results have been mapped to show the vulnerability distribution across Scotland and a display system for individual lakes has been proposed which allows a transparent and coherent structure that can shed light on distinct components of vulnerability, so that each can be evaluated individually, and in combination. This gives it an extremely strong basis for use by environmental managers interested in the climate change vulnerability of standing freshwaters in Scotland.

Chapter 5 – Adaptation strategies for freshwater conservation at multiple scales

5.1 Introduction

As climate changes become increasingly apparent, policy makers and site managers will be confronted with difficult choices to maintain biodiversity in line with national and international priorities (Sutherland *et al.* 2010; Crossman *et al.* 2012; Carter & White 2012; Whitman *et al.* 2013; Berry *et al.* 2015). Protected areas have been the dominant management strategy globally and will likely continue to be, given commitments of international environmental legislation (Hallegatte 2009; Lemieux & Scott 2011; Watson *et al.* 2014). Protected areas may comprise multiple management goals including the permanent protection of representative species and/or habitats, the maintenance of ecological integrity, and the provision of opportunities for education, research and recreation (Ervin & Congress 2003; Pittock *et al.* 2009; Fuller *et al.* 2010). Such approaches to conservation, designed to protect specific natural features, species, and ecological communities and processes in-situ, have not taken into account potential shifts in ecosystem composition, structure, and function that are anticipated to occur (Cadotte 2011; Villéger *et al.* 2013; Tomimatsu *et al.* 2013). Climate change impacts will likely affect whether or not these conservation management goals can be achieved in the long term (Heller & Zavaleta 2009; Nichols *et al.* 2011; McClure *et al.* 2013).

The mainstreaming of adaptation considerations into existing institutional decision-making processes can lead to policies that reduce vulnerability to climate change and better position environmental managers to exploit opportunities while simultaneously addressing other priorities (Lemieux & Scott 2011). There are a wide variety of stakeholders involved in environmental management of standing freshwaters at multiple spatial scales from international politics to site managers and users. This can present a challenge for adaptation as priorities and perceptions of different stakeholders can influence the willingness to adopt changing management practices (Dow *et al.* 2007; Hobbs 2009; Cook *et al.* 2013). Interdisciplinary methods drawing on social science can be utilised in environmental management to ellicit responses to complex options and uncertain futures (Mace *et al.* 2012; Sandbrook *et al.* 2013).

The need for adaptation strategies and actions beyond broad principles has been well documented (Wilby *et al.* 2010; Hall & Murphy 2011; Mawdsley 2011; Game *et al.* 2011; Ausden 2014). To date this has been limited and difficult to achieve with so much variety of system form and function and has led to a lack of action which has a number of potential roots. Firstly, the dominant scientific literature to date has originated from ecology and the natural sciences and has failed to engage with social science considerations such as decision-making, policy formation, participatory management or scenario setting (Heller & Zavaleta 2009). While the ecosystem services and ecosystem based management paradigms have attempted to promote more holistic approaches, the tendency remains to underrepresent cultural services leading to management objectives focusing primarily on biological or chemical indicators of system health (Schaich *et al.* 2010; Milcu *et al.* 2013; Jackson & Palmer 2015). Secondly, the high degree of uncertainty in traditional impact assessments makes them difficult for managers to translate them into practical management decisions (Dessai & Hulme 2007; Cross *et al.* 2012b). Finally, the conservation and climate change adaptation literature has not yet investigated the desirability or feasibility of adaptation options by those responsible for the planning and management of protected areas (Lemieux and others 2010). As Welch (2005) emphasized, this literature provides little guidance to the managers of already established protected areas and is a key area where this study can add value both specifically to the conservation management of Scotland's standing freshwater resource, and also wider management of similar resources globally.

This chapter aims to:

- Explore perceptions of climate change adaptation of those people engaged with conservation and environmental management of Scotland's standing freshwaters through research, policy or practical work.
- Rate the desirability, feasibility and multiple scales of action of 12 climate change adaptation strategies which cover a range of over 80 identified 'adaptation actions' potentially suitable for standing freshwater conservation management.

- Discuss what are the knowledge gaps and barriers to implementation for adaptation conservation policy in a changing climate.

5.2 Methods

5.2.1 Data collection

Social science methods allow a wide range of voices and experiences to be heard. Approaches like policy Delphi (Brooks *et al.* 2005; Lemieux & Scott 2011; Glass *et al.* 2013) are a way of combining multiple perspectives to solve complex problems, however they require long term and relatively high level engagement to be successful. An electronic survey structured in a similar fashion and informed by this discourse can hope to have similar impact, though the level of engagement is far removed and thus the potential to reach the depth of complex issues and engender practical action is reduced. Online surveys are relatively quick, cheap can allow multiple perspectives to emerge without any gatekeeper effect (Cook & Crang 2003) or influence from particularly vociferous workshop participants (Nairn 2005; Christoff 2010).

An online survey was created to collect data from a range of experts interested in climate change adaptation and freshwaters. Online surveys provide a range of advantages over more traditional methods including allowing access to unique populations, the high speed and low cost of data collection from participants located globally (Wright 2006).

Various online survey tools were trialled including BOS Survey, Survey Monkey, Lime Survey and Form Assembly. In each case the software had problems or excessive costs attached. Form Assembly allowed the use of channelling, conditional fields, required answers, likert ranking scales and unlimited data secured on the University's own servers without any associated cost and so was deemed the most suitable choice. The form was hosted on University of Dundee servers and was made accessible via a custom shortlink www.uod.ac.uk/adaptation (no longer live).

Data were collected from 15th October to 5th December 2013 using Form Assembly online survey tool licensed by the University of Dundee. The study was run with the full ethical approval of the University of Dundee Research Ethics Committee (reference UREC 13081). The full study protocol, participant information, consent declaration and outline question system can be found in Appendix B.

5.2.2 Participants

Respondents were self-selecting (they agreed to complete the survey without any influence) and were invited to contribute both via targeted email and social media accounts and more widely using relevant mailing lists. These individuals spanned research, policy and practitioners with participation from organisations including a number of universities and consultancies, the Scottish Government, Scottish Natural Heritage, Scottish Environment Protection Agency, Natural England, SNIFFER, Scottish Wildlife Trust, Centre for Ecology and Hydrology. Collectively they represented an inclusive array of perspectives from those involved in the environmental management of Scotland's standing freshwaters.

5.2.3 Survey Structure

The survey was designed in four sections, each displayed with pagination and a prompt displaying how far through the survey the participant has reached. This encourages users to complete the survey and minimises dropouts (Flowerdew and Martin 2005). The survey was intended to take 20-25 minutes to complete in total and while the majority of participants did manage to complete in this time period, the average completion time was considerably higher at 48 minutes with the longest submission time of over 18 hours, presumably because participants opened and returned to the survey over this time period.

5.2.3.1 Participant data

Section 1 collected personal data relating to the participants expertise, area and focus of work and general interests. This data provides context to the results and allows us to be confident that the respondents are indeed experts in fields and organizations relevant to the scope of this study.

5.2.3.2 Adaptation perceptions

Section 2 asked participants to rank a series of value statements using a likert scale (1-5, Strongly disagree to Strongly agree (Likert 1932)). The questions were designed to elicit an understanding of the perceptions of those involved in the environmental management of Scotland's standing freshwaters around five themes:

- The threat of climate change
- Knowledge of current resource
- Current conservation management techniques
- Future conservation priority
- Understanding of key terminology

5.2.3.3 Adaptation strategies

Section 3 asked respondents to rate desirability, feasibility and potential scale of action of 12 adaptation strategies. Adaptation actions specific to standing freshwater environments were identified using keyword and key phrase searches (c.f. Pullin & Stewart 2006) and literature review. Search terms focused around the keywords found in the published literature including ‘freshwater adaptation actions’; ‘lake adaptation action’; ‘climate change lake adaptation conservation’; ‘lake conservation climate change’. These actions were coded (Lindsay, 1997; Ritchie & Lewis, 2003) and subsequently clustered into 12 strategy groups to make it possible to engage survey respondents to approach the complex data collection surrounding the desirability and feasibility of these actions. These 12 strategy groups broadly connected to the 6 guiding adaptation principles after Hopkins *et al.* (2007): 1) conserve habitat and species baseline; 2) reduce sources of harm not linked to climate change; 3) develop ecologically resilient and varied landscapes; 4) establish ecological networks; 5) make sound decisions based on analysis; and 6) integrate adaptation and mitigation measures into conservation management, planning and practice.

For each adaptation strategy respondents were asked to first rate the desirability of the strategy (1-4, Very undesirable – Very desirable). To explore the feasibility of the adaptation strategy respondents were asked to rate a further four factors (Table 5.1).

Table 5.1: Scoring mechanism for desirability of each adaptation strategy where 1 = least desirable and 4 = most desirable

Affordability	Ease of implementation	Institutional capacity	Capacity to sustain over time
1 – Definitely Unaffordable	1 - Definitely not possible	1 - Definitely does not exist	1 - Definitely not possible
2 – Likely Unaffordable	2 - Likely not possible	2 - Significant investment required	2 - Likely not possible
3 – Likely Affordable	3 - Likely possible	3 - Resource reallocation necessary	3 – Likely Possible

4 – Definitely Affordable	4 - Definitely possible	4 - Capacity already exists	4 - Definitely possible

Finally, respondents were asked to score over which spatial and temporal scales the adaptation strategy should be actioned (Table 5.2).

Table 5.2: Scoring mechanism for spatial and temporal scale where 1 = the most local and short term solutions and 4 = the most global and long term.

Spatial Scale	Temporal Scale
1 – In the lake	1 - We should be/are doing this already 0-2 years
2 – In the catchment	2 - A priority over next 2-5 years
3 – Regional/National	3 - Could be a medium term goal 5-10 years
4 – International	4 - A long term solution 10+ years

5.2.3.3 Adaptation challenges

Section 4 asked participants to give open responses to a series of questions dealing with challenges facing climate change adaptation for conservation management.

5.2.4 Data Analysis

Data was exported from Form Builder software as comma separated values file (.csv), which was sorted and manipulated in Microsoft Excel before being imported to R as a tab delimited text file (.txt). All statistics were performed in R v2.12.1 (R core development team, 2014). Tables and figures were produced in Microsoft Excel, R and Adobe Illustrator.

To test whether or not there was a significant difference between question response and stakeholder role (A: Researcher, B: Practitioner, C: Policy maker) a Tukey's HSD test, with associated chi-squared test, was carried out using an analysis of variance (ANOVA) of the model "Question response~Stakeholder role" (Crawley, 2005). This test evaluates significant differences in pairwise comparisons of means for question responses given by participants within each of the stakeholder roles (Crawley, 2005; Bolker, 2008). This test was repeated for each section of the survey.

Adaptation strategies were considered 'Definitely feasible' if all four factors were scored as a positive response (3 or 4) by over 50% of participants. A strategy was considered 'Likely feasible' if 3 factors were scored positive by over 50% of participants with one factor being scored negative. Strategies which scored 2 factors as negative were considered 'Likely unfeasible' and strategies which scored 3 or 4 factors as negative were considered 'Definitely unfeasible'. To visualise these relationships, adaptation strategies were plotted across spatial and temporal scales in terms of strategy feasibility. Scale responses were also broken down by stakeholder group and visualised in terms of the intersection and overlap of stakeholder responses to adaptation strategies at multiple spatial and temporal scales.

Free text answers and comments from the survey were coded following standard procedures (Eyles, & Smith 1988; Mason 2002; Flowerdew and Martin 2005;).

5.3 Results

5.3.1 Participants

The survey was completed by 40 respondents representing a wide range of organisations including: the Scottish Government, Scottish Natural Heritage, the Scottish Environment Protection Agency, 17 universities and research institutes, and a number of NGOs and consultancies. The majority of participants were based in the UK (see Table 5.3). Participants were asked to self identify their current role and were grouped into three stakeholder groups – 26 identified as researchers, 8 as practitioners and 7 as policy makers (Table 6.2).

Table 5.3 - Country or region where participants work is currently based

Country or region	No.
Scotland	18
England	12
Wales	2
Ireland	1
Other European	2
International	5

Table 5.4 - Participants self identified stakeholder group

Current Role	No.	Stakeholder Group
Scientist/Researcher	25	A
Practitioner/Consultant/Site Manager	8	B
Policy Maker	7	C

Participants were also asked to self identify areas of professional interest (see Figure 5.1). Participants could select more than one option. On average participants selected 4 areas of interest. The most popular response was ‘Ecology’ (22 responses), followed by ‘Nature conservation’ (15 responses).

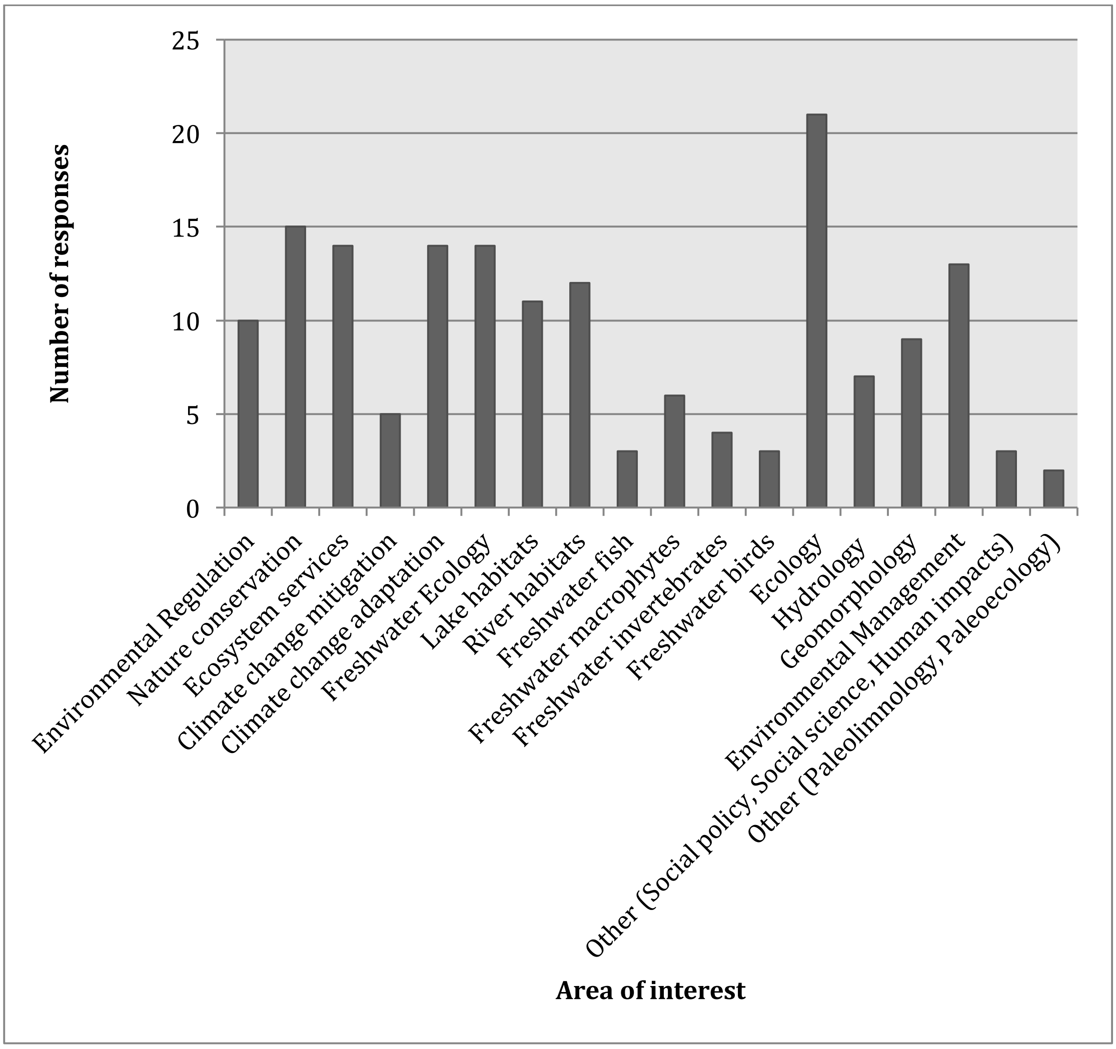


Figure 5.1 - Participants areas of interest

The participant group covers a wide range of interests and background within the intended scope of the survey and can be considered an excellent sample for this study.

5.3.2 Adaptation perceptions

Participants were asked to rate a series of positive intention statements (Kitchen and Tate 2000) using a likert scale (Likert 1932). The statements were structured around five main themes relating to the focus and priority of action and the need to adapt conservation management based on climate change exposure. Perhaps unsurprisingly, given the self-selecting nature of the survey (de Loe, 1995), the majority of respondents canvassed were broadly in agreement with the statements throughout (mean results in Figure 5.2) suggesting that the need for adaptation policies and actions is already a strong part of the environmental management discourse in Scotland.

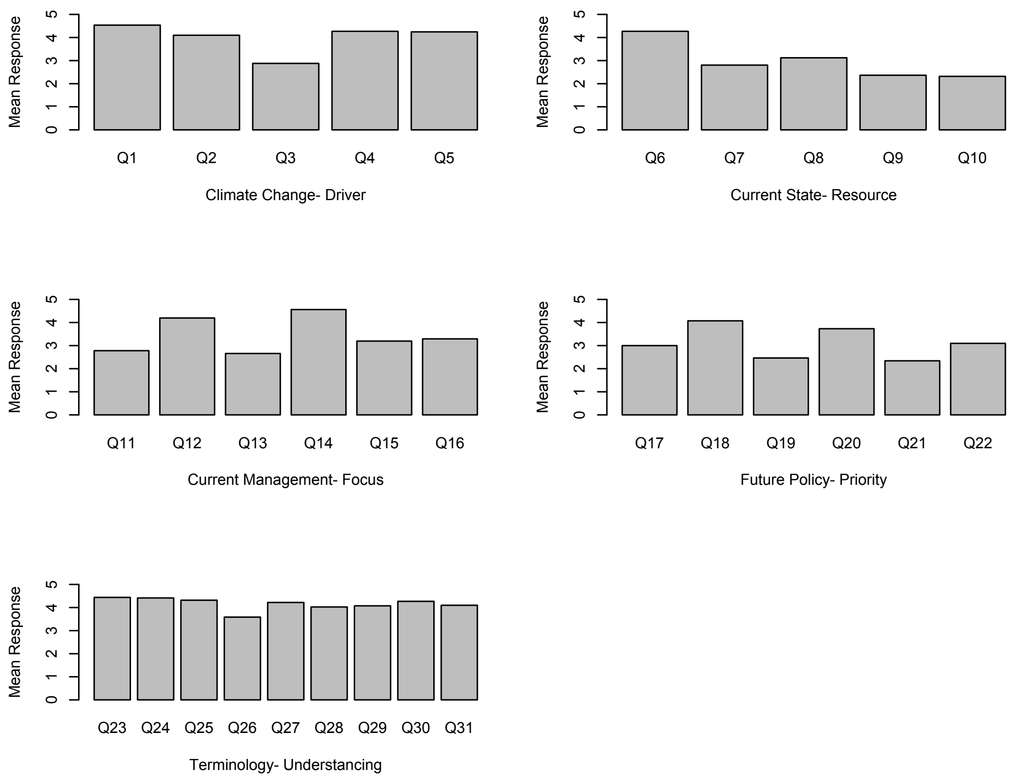


Figure 5.2 - Mean response rates to 31 positive intention statements scored using the Likert scale (1 – 5; Strongly disagree – strongly agree) grouped by broad topic.

Statements relating to climate change as a driver for changing conservation management (T1; Table 5.5) were met with a strongly positive response, with 97.5% of participants responding positively (Agree or Strongly Agree) to the statement 'Climate change adaptation must be a key part of any future conservation management plan' (Q1). Similar scores came for Q2, Q4 and Q5 with only Q3 (Understanding the range of climate model projections is not important; the important thing is to manage understanding there will be change) showing a level of disagreement across the participants.

Table 5.5 - Responses to positive intention statements T1 - Climate Change as a driver for changing conservation management (Q1-Q5)

			n	Mean	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree	Positive	Negative
Q1	T1: Climate Change - Driver	Climate change adaptation must be a key part of any future conservation management plans	40	4.65	67.5%	30.0%	2.5%	0.0%	0.0%	97.5%	0.0%
Q2		We should make decisions today based on the best possible climate model projections we have access to	40	4.20	40.0%	42.5%	15.0%	2.5%	0.0%	82.5%	2.5%
Q3		Understanding the range of climate model projections is not important; the important thing is to manage understanding there will be change	39	2.92	5.1%	28.2%	23.1%	41.0%	2.6%	33.3%	43.6%
Q4		Incorporating climate change adaptation into management plans is an opportunity to improve the way we work with the environment	40	4.38	40.0%	57.5%	2.5%	0.0%	0.0%	97.5%	0.0%
Q5		We should adapt conservation management, protected areas policy, system planning and legislation.	39	4.35	48.7%	41.0%	7.7%	2.6%	0.0%	89.7%	2.6%

Table 5.6- Responses to statements related to current state of the resource (T2; Q6-Q10)

			n	Mean	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree	Positive	Negative
Q6	T2: Current State - Resource	Freshwater lakes are an important part of Scotland's natural environment and worthy of increased management resource	40	4.38	57.5%	22.5%	20.0%	0.0%	0.0%	80.0%	0.0%
Q7		The current species assemblage in Scotland's lochs should be protected at all costs	40	2.88	7.5%	17.5%	37.5%	30.0%	7.5%	25.0%	37.5%
Q8		The current function(s) of Scotland's freshwater lakes should be protected at all costs	39	3.23	17.9%	23.1%	33.3%	15.4%	10.3%	41.0%	25.6%
Q9		We have sufficient data about Scottish freshwater species to manage our changing environment	40	2.43	2.5%	12.5%	22.5%	50.0%	12.5%	15.0%	62.5%
Q10		We have sufficient data about Scottish loch function to manage our changing environment	40	2.38	2.5%	12.5%	22.5%	45.0%	17.5%	15.0%	62.5%

Table 5.6 shows the second set of results relating to the current state of the resource and the current knowledgebase (T2; Q6-Q10). The greatest levels of disagreement throughout came with respect to current management practice, particularly issues surrounding current levels of knowledge. Over 60% of respondents disagreed or strongly disagreed with statements Q9 and Q10 relating to current knowledge of both system composition and function suggesting that more research or knowledge exchange is necessary in these areas (Martin *et al.* 2012; Cook *et al.* 2013).

The third group of statements related to current management practice and conservation focus (Table 5.7). Q11 and Q12 focus on the scale of management with agreement that conservation requires strong national and international legislation. Q14 (Ecosystems are dynamic and management should allow for change) was the only statement to get a 100% positive response indicating a strong willingness to engage with dynamic ecosystem based management which is often seen as a key facet of adaptation conservation management (Watson *et al.* 2011; Game *et al.* 2011; Ausden 2014). Q13 and Q16 ask participants about whether conservation management is proactive (Q13) or reactive (Q16). For adaptation to be successful it is likely that management will need to be proactive to adapt to uncertain futures (Nichols *et al.* 2011; Cross *et al.* 2012a). The results here indicate that this may be an issue for environmental managers in Scotland.

Table 5.7 - Responses to statements related to current management and conservation focus (T3; Q11-Q16)

			n	Mean	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree	Positive	Negative
Q11	T3: Current Management - Focus	Conservation can only be successful with intensive management at local/site level	40	2.85	10.0%	15.0%	35.0%	30.0%	10.0%	25.0%	40.0%
Q12		Conservation management requires strong legislation at the national / international level	40	4.30	45.0%	40.0%	15.0%	0.0%	0.0%	85.0%	0.0%
Q13		There is a willingness at all levels to employ proactive conservation management techniques	40	2.73	2.5%	17.5%	37.5%	35.0%	7.5%	20.0%	42.5%
Q14		Ecosystems are dynamic and management should allow for change	40	4.68	67.5%	32.5%	0.0%	0.0%	0.0%	100.0%	0.0%
Q15		Ecosystem services are the key framework for understanding the value of Scotland's natural environment	39	3.26	5.1%	43.6%	33.3%	7.7%	10.3%	48.7%	17.9%
Q16		Conservation management is, by it's very nature, reactive to change	40	3.38	10.0%	40.0%	27.5%	22.5%	0.0%	50.0%	22.5%

Table 5.8 shows the response rates related to future management policy. Participants responded particularly positively to statement Q18 (Ecosystem based management should be a priority). There was disagreement with two statements Q19 and Q21 with a neutral response to Q22. These statements relate to future conservation priority and the responses here indicate that there is a lack of cohesion around what are difficult and potentially controversial decisions.

Table 5.8 - Responses to statements related to future conservation management policy and priority (T4; Q17-Q22)

			n	Mean	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree	Positive	Negative
Q17	T4: Future Policy - Priority	Conservation of current species assemblage is priority	38	3.13	2.6%	47.4%	13.2%	34.2%	2.6%	50.0%	36.8%
Q18		Ecosystem based management should be a priority	39	4.18	33.3%	53.8%	10.3%	2.6%	0.0%	87.2%	2.6%
Q19		Highly vulnerable systems/species should not be protected - limited resources should focus on those areas with a reasonable chance of longer term resilience.	40	2.53	0.0%	17.5%	30.0%	40.0%	12.5%	17.5%	52.5%
Q20		Ecosystem service provision should be explicitly incorporated into protected area/conservation management goals	40	3.83	22.5%	45.0%	25.0%	7.5%	0.0%	67.5%	7.5%
Q21		Highly stressed or poor quality systems/species should no longer be protected - limited resources should focus on areas with a reasonable chance of longer term resilience.	40	2.40	0.0%	12.5%	20.0%	62.5%	5.0%	12.5%	67.5%
Q22		Highly vulnerable, disjunct/relict, and outlier systems/species should receive higher protection priority in conservation planning.	39	3.21	2.6%	33.3%	46.2%	17.9%	0.0%	35.9%	17.9%

Table 5.9 - Responses to statements related to participants' knowledge of key terminology and understanding (T5; Q23-Q31)

			n	Mean	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree	Positive	Negative
Q23	T5: Terminology - Understanding	Adaptation	40	4.55	57.5%	40.0%	2.5%	0.0%	0.0%	97.5%	0.0%
Q24		Mitigation	40	4.53	55.0%	42.5%	2.5%	0.0%	0.0%	97.5%	0.0%
Q25		Resilience	38	4.42	52.6%	39.5%	5.3%	2.6%	0.0%	92.1%	2.6%
Q26		Exposure	39	3.67	33.3%	23.1%	20.5%	23.1%	0.0%	56.4%	23.1%
Q27		Sensitivity	39	4.33	48.7%	41.0%	5.1%	5.1%	0.0%	89.7%	5.1%
Q28		Adaptive Capacity	39	4.13	41.0%	35.9%	17.9%	5.1%	0.0%	76.9%	5.1%
Q29		Adaptive Management	39	4.18	41.0%	43.6%	7.7%	7.7%	0.0%	84.6%	7.7%
Q30		Vulnerability	39	4.38	46.2%	48.7%	2.6%	2.6%	0.0%	94.9%	2.6%
Q31		Ecosystem Based Management	39	4.21	38.5%	48.7%	7.7%	5.1%	0.0%	87.2%	5.1%

The final group asked participants to rate how confident they were with a range of key terminology. Understanding of all key terminology was very high, with no 'Strongly Disagree' to any of the 9 terms (T5; Q23-Q31). Again this highlights that the survey participants are very well suited to task. It also indicates that the key terms used throughout this study are well known to conservation managers in Scotland, which again implies that climate change adaptation is high on the environmental management agenda for ecology researchers, practitioners and policy makers.

The question remains whether the different backgrounds of the respondents led to different responses to the statements between stakeholder groups. A significantly different response between stakeholder users was observed for only six of the statements. When participants were asked to score the statement Q1 (Climate change adaptation must be a key part of any future conservation management plans) researchers (A) and practitioners (B) gave significantly different responses, with researchers agreeing more strongly with the statement (p=0.01, Figure 5.3: Q1). When asked Q5 (We should adapt conservation management, protected areas policy, system planning and legislation) researchers (A) and policy makers (C) gave significantly different responses, with policy makers agreeing more strongly with the statement (p=0.004), Figure 5.3: Q5). When asked Q11 (Conservation can only be successful with intensive management at local/site level) researchers (A) and policy makers (C) gave significantly different responses, with policy makers disagreeing more strongly with the statement (p=0.024), Figure 5.3: Q11). The final three statements showing a significant difference were related to the key terminology Q23 (Adaptation), Q24 (Mitigation) and Q26 (Exposure). In each case the difference was between practitioners (B) and policy makers (C) with policy makers being more confident in key terminology in each case.

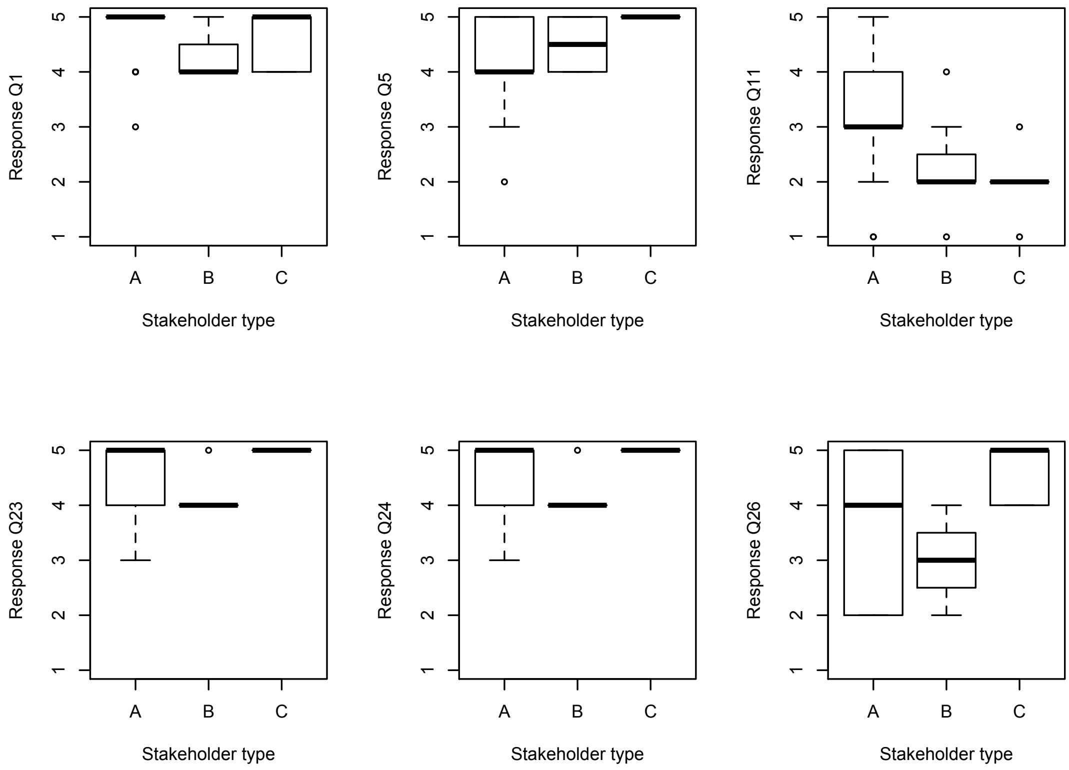


Figure 5.3 – Responses showing the mean, interquartile range and outliers for 6 statements where there were significant differences between stakeholder type A (Researchers), B (Practitioners) and C (Policy Makers).

5.3.3 Adaptation Strategies

As has been discussed previously there are few published papers that go beyond broad adaptation principles to specific actions (Wilby *et al.* 2010; Morecroft *et al.* 2012). Of those identified, Lemieux & Scott (2011) offered the greatest number of actions across a wide range of environmental management practices focused in particular on protected area management and governance in Canada. Other notable papers included Ormerod 2009; Pittock *et al.* 2009; Heller & Zavaleta 2009; Clarke 2009; Nel *et al.* 2009; Wilby *et al.* 2010; Barmuta *et al.* 2011; Mawdsley 2011 and Khamis *et al.* 2013. Over 200 actions were identified from these papers of which over 80 were appropriate for standing freshwaters. Each adaptation strategy and the associated actions are described in full below in Table 5.10.

Table 5.10 - Potential climate change adaptation actions for the conservation interest of Scotland's standing freshwaters

Adaptation Principle	Adaptation Strategy	Adaptation Actions
1 - Conserve habitat and species baseline	1 - Implement a full scale protected area system review	• Identify the role of each protected area in contributing to ecological representation/functional requirements - does the current protected area system adequately protect the variety of Scotland's freshwater environments? • Review protected area classifications and change if necessary to accommodate changing protection values. For example, some areas originally established for recreation purposes may emerge to be more valuable for the protection of natural assets, such as species at risk and potentially vice versa. • Include climate change considerations in policies on modifying protected area boundaries and designing ecologically appropriate boundaries. • Explore de-regulating parks as an option should a protected area no longer achieve its original protection mandate. • Incorporate redundancy into protected areas system planning requirements to offset potential species losses resulting from climatic and ecological change (giving high priority to species at risk and highly threatened species). • Build climate change indicators into existing monitoring programs and ecological integrity monitoring frameworks and explicitly link to management goals. • Reassess ecological representation and function as part of the protected area planning process review at five to ten year intervals (i.e., the overall landscape of Scotland will be changing, and so must the role of each location)
	2 - Practice proactive intensive species management to secure priority populations	• Continue to fund current protected area system. • Manage this system increasing connectivity where possible including assisted migrations and proactive habitat management. • Consider assisted migration and species translocation as an active management option when species are unable to migrate to suitable habitat naturally. • Create a translocation action plan for those species currently deemed at high risk, identifying potential translocation sites. • Policies and targets should not only address elements of biodiversity pattern, but should also include the spatial and temporal aspects of natural processes, including population sizes, movements, metapopulation dynamics, disturbance regimes, ecological refugia, phenotypic placticity, local adaptation and evolutionary responses to climate change. • Identify suitable habitat areas (and/or create new reservoirs) for translocation of species of high conservation priority already under threat particularly where identified species cannot migrate naturally. Ex-situ conservation measures may need to be considered. • National agencies (eg SNH) should maintain up-to-date distribution maps of species and communities, which should be shared openly.

2 - Reduce sources of harm not linked to climate change	3 - Mitigate other threats including invasive species, habitat fragmentation and pollution	• Invest in long term catchment management solutions to reduce point and, importantly, diffuse pollutants, in protected / priority areas. • Identify poorly functioning systems and reconnect wetlands where possible. • Proactively target invasive species making use of citizen science / conservation volunteers to control / remove. • Invasive species management direction should be fluid and include new and upcoming invasives that could expand their range and affect ecological integrity because of climate change. • Increased effort to use natural ecological processes (e.g., fire, prescribed burns) to control invasives. • Mandatory check-points and cleaning stations to ensure boats/recreational users are clean of non-native/invasive species prior to their launch in a protected/priority area should be installed. • There is an increasing need to take a precautionary approach to environmental management as uncertainty increases with climate change. This is particularly true in the context of cumulative impacts. As such, the precautionary approach should be explicitly built into policy, planning and management.
	4 - Create ecosystem based catchment management plans for all of Scotland's freshwater systems	• 'Soften' landuse practices in priority catchments: Land use activities adjacent to protected/priority areas should allow for movement of wildlife and plants and help to feather conservation interest into the working landscape. • Enforce buffers around lakes: Policy and regulations should ensure that land uses adjacent to protected areas do not compromise integrity and connectivity functions. • Fund more farming liasons and positive intervention strategies offering funded alternatives and positive solutions rather than penalties. • Fisheries management should place more emphasis on maintaining cold-water aquatic ecosystems and the species that depend on them. • Areas adjacent to vulnerable lakes should generally not be developed, and natural vegetative cover should be maintained or restored. • Shoreline erosion restoration (e.g., enhancing riparian vegetation cover) should be used to enhance and prolong cool water species habitats. Restoration and re-vegetation activities should use native species and grasses only.

3 - Develop ecologically resilient and varied landscapes	5 - Create a new, lake specific, protected area network	• Use climate change agenda as catalyst to accelerate the process of establishing additional protected areas. • Create a new, lake specific, protected area network based not on chemical / trophic / species status but on lake function. • Create new reservoirs specifically for the translocation and conservation of endangered priority species. • Future protected area establishment should focus on species at the northern limits of their range as these may be the best adapted to adjust to changing climatic conditions. • 'Floating' protected areas, temporal reserves and protected areas swapping approaches (i.e., strategic de-regulation and establishment) should be explored as a planning option in order facilitate the movement of non-migratory species and increase the overall resiliency of the protected areas system to climate change related impacts. • Protected areas system design should more effectively incorporate persistence parameters to ensure perpetual representation (i.e., representation through time), anticipate locations that could serve as refugia for certain kinds of ecosystems and work to protect these sites in advance. • Clustered management plans that would provide a generic management prescription for a series of protected areas having similar ecological management should be used to provide the flexibility needed to incorporate climate change considerations at local and regional levels. • Make assessments of ecological integrity relative the prevailing climate at the time of assessment and not a historical benchmark that no longer exists.
	6 - Manage reserves for complex, non-linear, changes and 'landscape asynchrony'	• Create a lake specific habitat action plan highlighting best practises. • Manage for flexibility using portfolio of approaches to maintain options increasing resilience + resistance to change eg. Shoreline 'naturalisation' and potential management options including in lake mechanisms - (cold water discharge, aeration pumps, creation of deep/cold water refugia). • Maintain (encourage) natural disturbance dynamics. • Each protected area management plan should specifically address how climate change is likely to affect ecological integrity and provide management direction to help address the issues. • Increase and maintain monitoring and evaluation processes and practise adaptive management - action plans must be time bound and measurable. • System planning should focus more on inherent capability (e.g., soils, water, productivity) and less on the current occupancy of flora and fauna (i.e., permanent features vs. impermanent ones). • Live bait should be severely restricted, or regulated against, in order to avoid the spread of invasive species.
	7 - Invest in ecosystem based management including catchment restoration within both populated and wild landscapes	• Water levels should not be maintained at artificially high or low levels, aspiring towards a natural flow. Wetlands should be reconnected to river flood plains and standing freshwaters. • Anthropogenic lakes which connect to cold water systems and have a warming influence should be reduced or eliminated. • Anthropogenic lakes and ponds should be disconnected and returned to natural bathymetry. • Current uses of high intensity recreational sites may need to be altered (decreased, stopped). • Built structures such as docks and boathouses at lake level should be avoided. Permanent docks should be replaced by floating docks to facilitate annual relocations subject to water levels and to reduce impacts on aquatic habitats.

4 - Establish ecological networks	8 - Establish an ecological lake network in Scotland	• Increase connectivity between lakes - design corridors, identify & remove barriers to dispersal, locate reserves close to each other or on identified migration routes. • Consider longitudinal (North/South) connectivity of particular importance. • A comprehensive network monitoring system should be implemented. • Fund research to identify what an ecological network of lakes should look like in Scotland. This should be created with climate change adaptation firmly in mind - based on function / form / resilience and not current species assemblage etc. • Increase the planning boundaries around current protected areas / priority sites to increase buffer spaces and prioritise riparian corridors along river/lake banks.
5 - Make sound decisions based on analysis	9 - Re-assess current conservation goals	• Open the debate about Scotland's future environment - integrate with media / online space for open discussion of the issues surrounding what society wants and needs from its freshwater environment over the coming century. • Some of the broad guiding principles incorporated into protected area policy, such as representation and permanence, should be re-evaluated in light of climate change. • Future policy reviews should consider redefining the concept of ecological integrity. • Acceptable rates of change and defining what exactly constitutes species characteristic of a natural region should be more explicitly defined with climate change considerations in future policy. • Ecological representation should no longer be used as criteria (the others being condition, diversity, ecological functions, and special features) for selecting and designing protected areas. • Move management focus from WFD 'poor' to 'good' systems - open discussion at WFD level. More generally accept losses to focus on potential gains. • Reconsider the basic definitions of non-native and invasive species. New definitions should include climate change considerations. Rules for acceptance of non-native species as part of the ecosystem need to be developed. • A research strategy should be developed on the role of protected areas and climate change (e.g., What are the looming questions needing answers necessary to address critical policy, planning, management and operation needs in protected areas? More broadly, what service roles can protected areas play as platforms for long-term time-trend research on climate change issues that transcend protected areas?).
	10 - Fund more (interdisciplinary) study on priority and indicator species / function, long term changes, climate impacts	• Invite top species specialists to produce a 'top priorities' list of potential research. Create funding to look specifically at the issues raised. • Invest in research into the following topics: species distribution modelling & GIS; migration rates and historic flux at multiple spatial & temporal scales; dispersion capability, barriers and gene flow; social use and valuation of high priority species/systems. • A multi-disciplinary team should be engaged to examine the ecological representation criterion for selecting and designing protected areas, evaluate whether this approach is viable in protecting biodiversity under a changing climate, and examine alternative approaches to protected areas systems planning. • Establish long-term research and monitoring sites against which to quantitatively measure climate change impacts. Increase climate change trend modelling studies (e.g., with regards to species composition, water quality and quantity, invasive species, pests and diseases, local and regional climate, species at risk, threatened species, etc.) to assess potential future impacts on protected areas assets.

		• A comprehensive research strategy and monitoring framework with a defined set of measures (with sufficient spatial and temporal considerations) pertaining to climate change should be established at both the site and protected area system level to track climate change and its effects and for comparative reporting. • Develop specific thresholds related to climate change that trigger management actions if the state of ecological integrity is assessed to be declining. • Research strategies should be reviewed to include the ability of species to recover from climate change disturbances and repeated disturbances (i.e., both resistance and resilience to change). • Monitoring sites should be established in the least disturbed protected areas to act as control sites for projects investigating the effects of climate change. Monitor long-term changes in species composition using permanent sample/systematic plots located at ecotones (species at the northern limits of their range).
6 - Integrate adaptation and mitigation measures into conservation management , planning and practice	11 - Promote a new environmental management culture with climate change adaptation, improved inter-agency cooperation and regional coordination at its core.	• Create a national working group featuring freshwater specialists from SNH/SEPA/NGOs/Universities etc to meet regularly with the particular focus on adaptation management for freshwater conservation. • A specific monitoring strategy should be developed related to climate change to detect and monitor trends and impacts. Monitoring efforts should be coordinated across jurisdictions and with other organizations and partners (i.e., standardize indicators, protocols, etc. to enable seamless roll-ups, assessment, and reporting of time-trend data). • Management plans should be reviewed once specific thresholds related to climate change are exceeded (e.g., changes in species populations or temperature regimes). Environmental assessments should incorporate climate change considerations. • SNH / SEPA should ensure that all staff have a level of understanding of, and capacity to respond to, climate change impacts and adaptation appropriate to their mission. There should be more opportunities for staff to participate in climate change workshops and engage with experts in the field to keep abreast of new climate change related developments. • Protected areas organisations should work in cooperation with other organisations outside of protected area boundaries to help reduce the impacts of climate change through approaches such as protected area system design, ecological restoration and compatible land uses adjacent to protected areas. • A regular conference or series of workshops across the country to bring together partners involved in conservation management to discuss and learn from leading edge researchers and practitioners who have been considering climate change adaptation and how to integrate it into protected areas planning and management should be developed.
	12 - Adopt long term and regional perspective in planning, modelling and management	• Promote conservation policies which engage local users and promote healthy human communities. • Make use of multiple communication channels (print and traditional visual/audio media, academic journals, websites and social media) to report on climate impacts and trends to a wide variety of audiences. • Management plans should incorporate a long-term trends analysis to help guide longer-term actions and priorities. • Principles of adaptive management and the ecosystem approach should be incorporated into all management (e.g., preparing and implementing resource management plans and their subset of interventions) and planning (strategic/corporate, systems planning, site level management plans) directions. • Adaptation to operations and development should be idiosyncratic in nature and will need to be evaluated on a regional, or even site by site, basis because many other variables will also need to be evaluated (e.g., water control structures, cost-benefit analysis, risk analysis). • The role of visitors and volunteers in preventing, monitoring, and managing invasive species should be addressed in management planning.

- Caps on usage of facilities such as trails to proactively ensure that excessive and extended use in the future does not create additional stresses on these ecosystems. Facilities that may no longer be viable under changing climatic conditions need to be identified and managed.
- An integrated and cooperative monitoring strategy related to climate change to detect and monitor trends and impacts, especially for regionally threatened species, extinction prone species, and management target species, should be established and implemented at the ecoregion/system level. Such a monitoring program should also be used to document and assess the success/failure of remedial actions.
- Staff and volunteer monitoring programs (e.g., NGOs, 'Friends Of' groups, local schools, park users, etc.) to detect and monitor climate change impacts should be established by regional offices, and individual protected areas.
- Regular reporting on climate change monitoring results and adaptation activities via scientific literature, grey literature, and the popular literature to inform stakeholders and help garner support for funding and staffing.
- Conservation organisations should provide input into the development of primary and secondary school curriculum (e.g. develop lesson plans that teachers could use in the classroom).
- Protected areas should lead by example in public interpretation and education activities. Protected areas should be used to educate the public (e.g. through interpretation activities) about climate change impacts and the implications of these impacts for park features (e.g. species, habitats, ecoregions, physiography, etc.) and to build public support on climate change initiatives. Protected areas should be used to inform the public about climate change and efforts to mitigate and adapt to it.
- Climate change issues awareness messages should be incorporated into virtually every public communication tool available to environmental management (e.g. interpretative packages, publications such as fact sheets, tabloids and park guides, websites, DVDs etc).

5.3.3.1 – Strategy Desirability

Each of the 12 strategies proposed here were considered desirable (see Table 9) with four strategies scored ‘Most desirable’ (3,4,11,12; positive responses above 90%), four strategies scored ‘Very desirable’ (1,2,6,10; 80-90% positive) and four strategies scored ‘Desirable’ (5,7,8,9; 70-80% positive).

Table 5.11 - Desirability of 12 proposed adaptation strategies. 4 = Very Desirable – 1 = Very Undesirable. All adaptation strategies were considered desirable.

Adaptation Strategy	**n**	**4**	**3**	**2**	**1**	**+**	**-**	**Desirability**
1 - Implement a full scale protected area system review	38	24%	63%	5%	8%	87%	13%	**Very Desirable**
2 - Practice proactive intensive species management to secure priority populations	37	30%	57%	11%	3%	86%	14%	**Very Desirable**
3 - Mitigate other threats including invasive species, habitat fragmentation and pollution	37	65%	30%	0%	5%	95%	5%	**Most Desirable**
4 - Create ecosystem based catchment management plans for all of Scotland's river systems	33	58%	36%	6%	0%	94%	6%	**Most Desirable**
5 - Create a new, lake specific, protected area network	32	13%	59%	28%	0%	72%	28%	**Desirable**
6 - Manage reserves for complex, non-linear, changes and 'landscape asynchrony'	33	24%	58%	15%	3%	82%	18%	**Very Desirable**
7 - Invest in ecosystem based catchment restoration	33	21%	48%	18%	12%	70%	30%	**Desirable**
8 - Establish an ecological lake network in Scotland	32	28%	47%	19%	6%	75%	25%	**Desirable**
9 - Re-assess current conservation goals	31	35%	39%	19%	6%	74%	26%	**Desirable**
10 - Fund more (interdisciplinary) research	33	33%	55%	6%	6%	88%	12%	**Very Desirable**
11 - Harness a new environmental management culture with climate change adaptation at its core	30	57%	37%	3%	3%	93%	7%	**Most Desirable**
12 - Adopt long term and regional perspective in planning, modelling and management	31	58%	39%	0%	3%	97%	3%	**Most Desirable**

Strategy 3 (mitigating other threats) was most desirable with 95% positive response (65% of respondents answering 'Very Desirable'). Strategies 4 (Create ecosystem based catchment management plans for all of Scotland's river systems), 11 (Harness a new environmental management culture with climate change adaptation at its core) and 12 (Adopt long term and regional perspective in planning, modelling and management) had similarly high desirability with over 90% positive responses. The least positive response was to strategy 7 (Invest in ecosystem based catchment restoration) with 30% negative responses (12% Very Undesirable). This strategy saw the only significantly different response between stakeholder groups. Researchers (A) and Policy Makers (C) gave significantly different response, with Researchers finding the strategy 'Desirable' and Policy Makers 'Very Undesirable' (p=0.004; Figure 5.4). Strategies 5, 8 and 9 also had slightly negative responses but in each case the overall response rate was over 75% positive. The mean responses are plotted in Figure 5.5 for all 12 strategies.

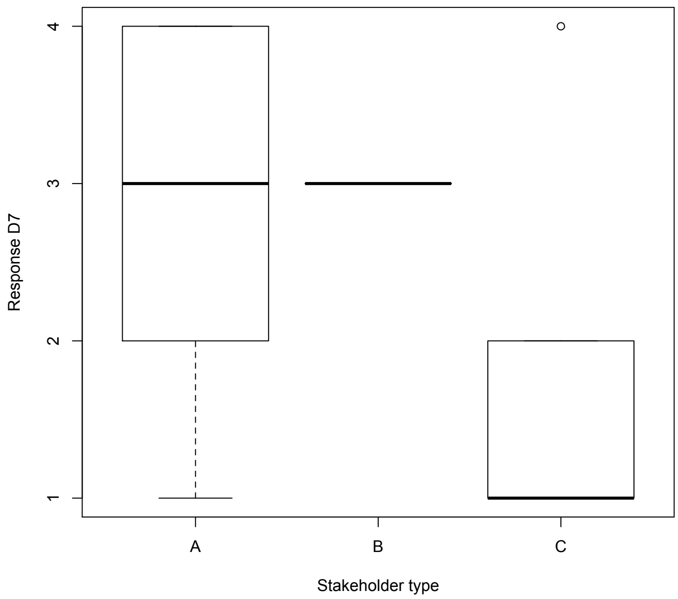
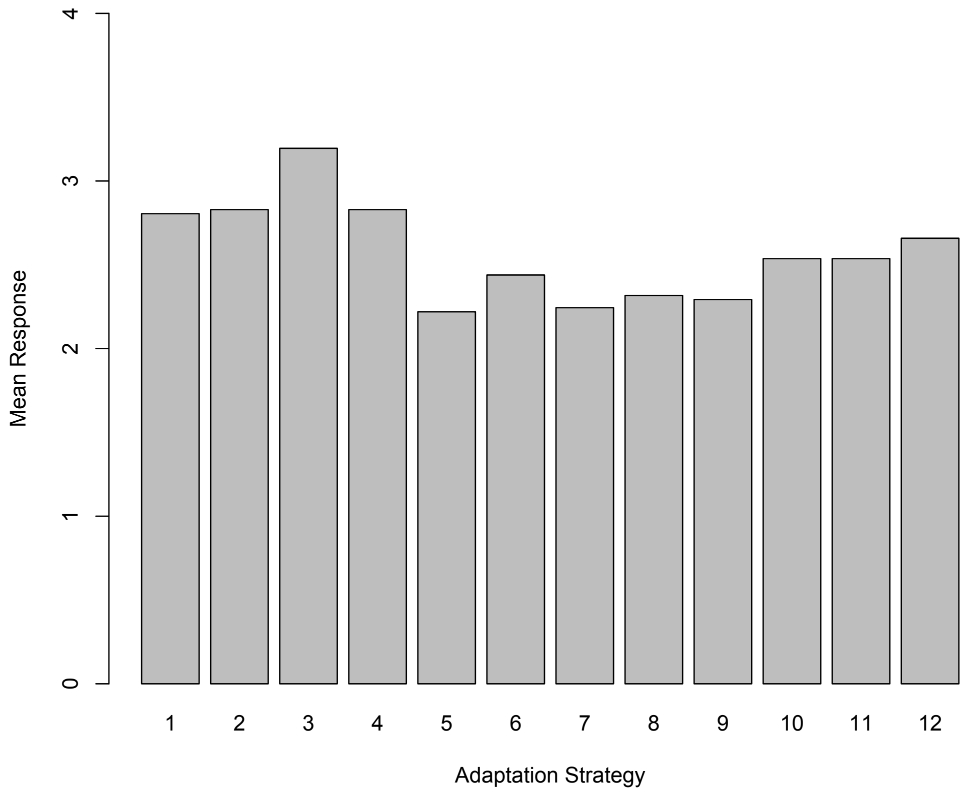


Figure 5.4 - Strategy 7 (Invest in ecosystem based catchment restoration) responses showing the mean, interquartile range and outliers. Stakeholder type A (Researchers) and C (Policy Makers) have significantly different response to this strategy (p=0.004)



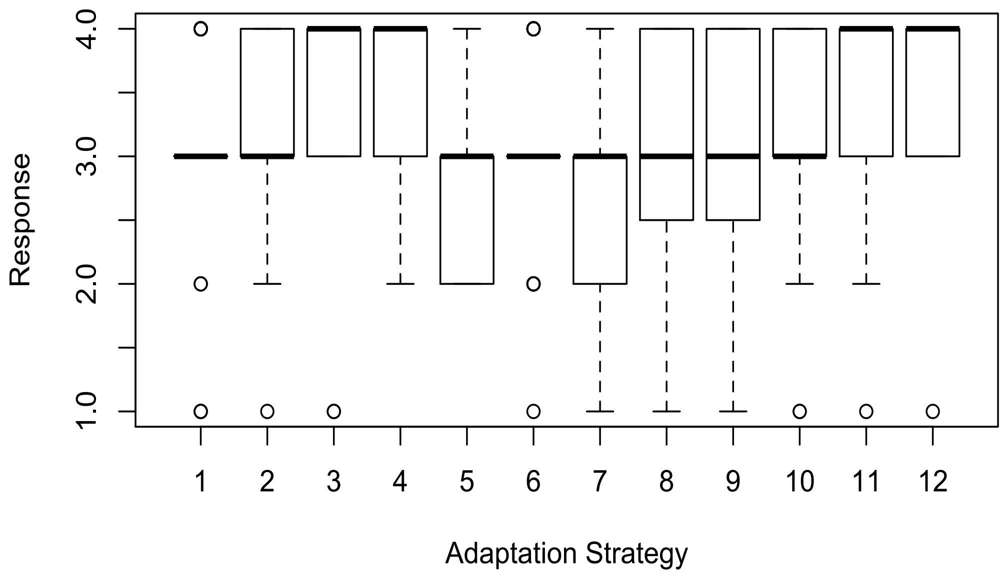


Figure 5.5 - Mean response scores for 12 conservation adaptation strategies. Results displayed as a standard histogram, above, and below as a box plot showing the mean, inter-quartile range, standard error and outliers. All strategies were considered desirable.

5.3.3.2 – Strategy Feasibility

For an adaptation strategy to be successfully implemented it is likely that the strategy will be both desirable and feasible (Lemieux & Scott 2011). Feasibility is a more complex concept however, which needs to take into account a number of aspects including whether the strategy is affordable, the ease of implementation, whether institutional capacity exists and the ability to sustain that investment over time (Lemieux & Scott 2011; Doswald *et al.* 2014; Whitehead *et al.* 2014). Figure 5.6, below, outlines the scoring patterns across all 12 adaptation strategies and the calculated feasibility. Mean scores across each factor are shown in Table 5.12. In total six strategies are considered 'Definitely feasible' (1,3,4,9,11,12), four are considered 'Likely feasible' (2,5,6,10), one is considered 'Likely not feasible' (8) and one is considered 'Definitely not feasible' (7). 'Institutional capacity' is in every case the factor that is most negatively scored.

Table 5.12 - Feasibility scores for 12 adaptation strategies. Participants were asked to score the affordability, ease of implementation, institutional capacity and capacity to sustain the strategy and actions over time. Six strategies are scored definitely feasible.

		n	4	3	2	1	+	-	F
1 - Implement a full scale protected area system review	Affordability	36	8%	50%	42%	0%	58%	42%	**Definitely Feasible**
	Ease of implementation	36	11%	69%	19%	0%	81%	19%	
	Institutional capacity	36	17%	33%	44%	6%	50%	50%	
	Capacity to sustain over time	36	6%	67%	22%	6%	72%	28%	
2 - Practice proactive intensive species management to secure priority populations	Affordability	33	6%	70%	18%	6%	76%	24%	**Likely Feasible**
	Ease of implementation	33	6%	67%	27%	0%	73%	27%	
	Institutional capacity	33	9%	39%	45%	6%	48%	52%	
	Capacity to sustain over time	33	9%	61%	30%	0%	70%	30%	
3 - Mitigate other threats including invasive species, habitat fragmentation	Affordability	33	21%	58%	21%	0%	79%	21%	**Definitely Feasible**
	Ease of implementation	33	27%	45%	24%	3%	73%	27%	
	Institutional capacity	33	12%	45%	33%	9%	58%	42%	

and pollution	Capacity to sustain over time	33	21%	58%	21%	0%	79%	21%	
4 - Create ecosystem based catchment management plans for all of Scotland's freshwater systems	Affordability	32	13%	72%	13%	3%	84%	16%	**Definitely Feasible**
	Ease of implementation	32	13%	59%	25%	3%	72%	28%	
	Institutional capacity	32	19%	38%	38%	6%	56%	44%	
	Capacity to sustain over time	32	16%	63%	19%	3%	78%	22%	
5 - Create a new, lake specific, protected area network	Affordability	27	11%	52%	33%	4%	63%	37%	**Likely Feasible**
	Ease of implementation	27	7%	56%	37%	0%	63%	37%	
	Institutional capacity	27	19%	22%	48%	11%	41%	59%	
	Capacity to sustain over time	27	15%	56%	22%	7%	70%	30%	
6 - Manage reserves for complex, non-linear, changes and 'landscape asynchrony'	Affordability	29	10%	48%	38%	3%	59%	41%	**Likely Feasible**
	Ease of implementation	29	7%	59%	28%	7%	66%	34%	
	Institutional capacity	29	17%	28%	45%	10%	45%	55%	
	Capacity to sustain over time	29	10%	52%	31%	7%	62%	38%	
7 - Invest in ecosystem based catchment restoration	Affordability	30	7%	40%	43%	10%	47%	53%	**Definitely Not Feasible**
	Ease of implementation	30	13%	33%	47%	7%	47%	53%	
	Institutional capacity	30	10%	27%	50%	13%	37%	63%	
	Capacity to sustain over time	30	17%	47%	30%	7%	63%	37%	
8 - Establish an ecological lake network in Scotland	Affordability	30	10%	47%	37%	7%	57%	43%	**Likely Not Feasible**
	Ease of implementation	30	10%	50%	33%	7%	60%	40%	
	Institutional capacity	30	7%	7%	70%	17%	13%	87%	
	Capacity to sustain over time	30	13%	47%	33%	7%	60%	40%	
9 - Re-assess current conservation goals	Affordability	27	30%	52%	15%	4%	81%	19%	**Definitely Feasible**
	Ease of implementation	27	22%	56%	19%	4%	78%	22%	
	Institutional capacity	27	37%	30%	22%	11%	67%	33%	
	Capacity to sustain over time	27	33%	48%	15%	4%	81%	19%	

10 - Fund more (interdisciplinary) research	Affordability	30	10%	53%	33%	3%	63%	37%	**Likely Feasible**
	Ease of implementation	30	23%	60%	13%	3%	83%	17%	
	Institutional capacity	30	20%	27%	50%	3%	47%	53%	
	Capacity to sustain over time	30	20%	60%	17%	3%	80%	20%	
11 - Harness a new environmental management culture with climate change adaptation at its core	Affordability	28	25%	50%	25%	0%	75%	25%	**Definitely Feasible**
	Ease of implementation	28	25%	57%	14%	4%	82%	18%	
	Institutional capacity	28	25%	32%	39%	4%	57%	43%	
	Capacity to sustain over time	28	39%	46%	14%	0%	86%	14%	
12 - Adopt long term and regional perspective in planning, modelling and management	Affordability	28	39%	57%	4%	0%	96%	4%	**Definitely Feasible**
	Ease of implementation	28	39%	50%	7%	4%	89%	11%	
	Institutional capacity	28	36%	39%	21%	4%	75%	25%	
	Capacity to sustain over time	28	43%	50%	7%	0%	93%	7%	

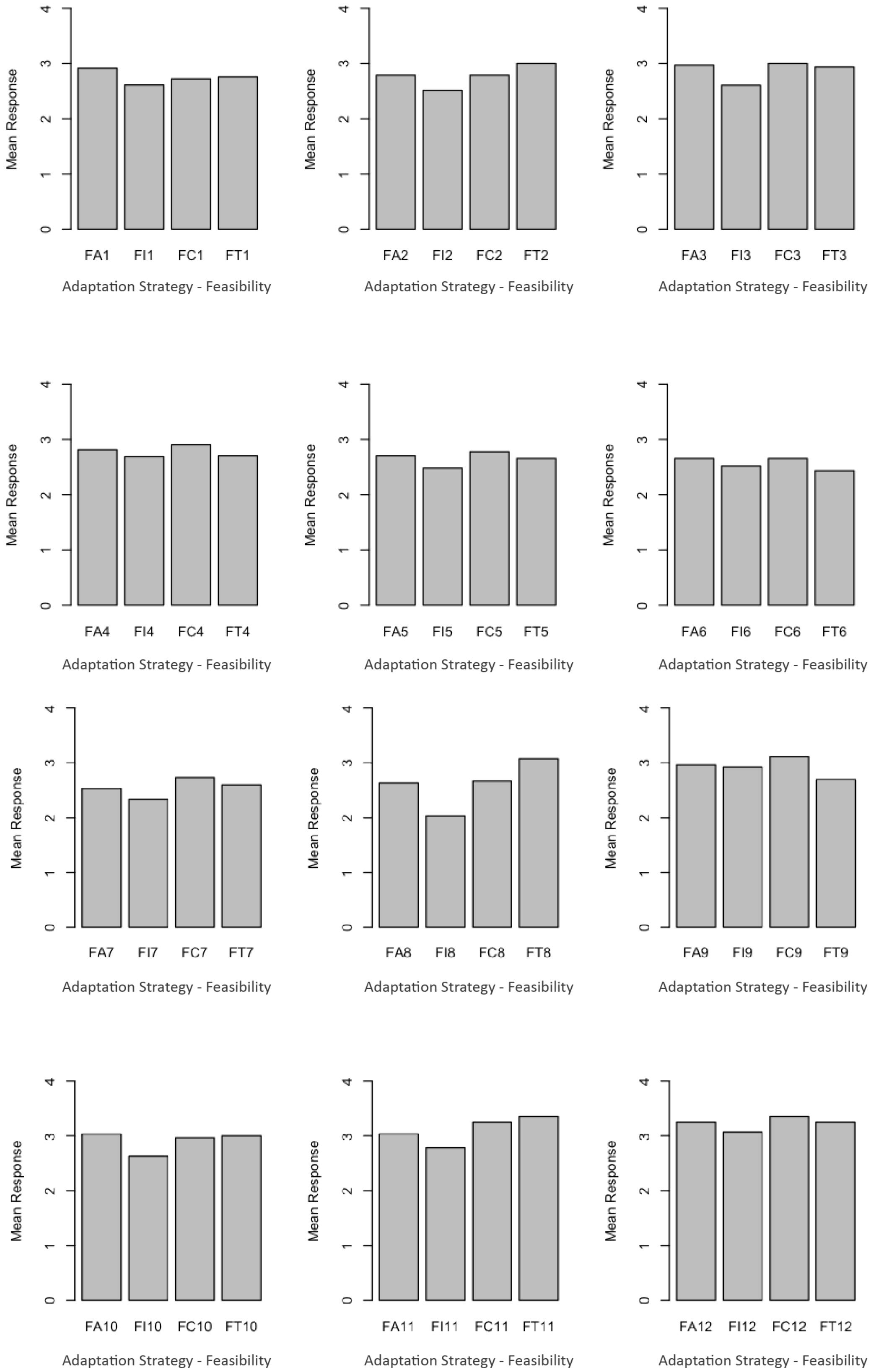


Figure 5.6 - Mean scores of all survey participants for each adaptation strategy (1-12) and each feasibility factor (FA - affordability, FI - ease of implementation, FC - institutional capacity and FT - capacity to maintain over time).

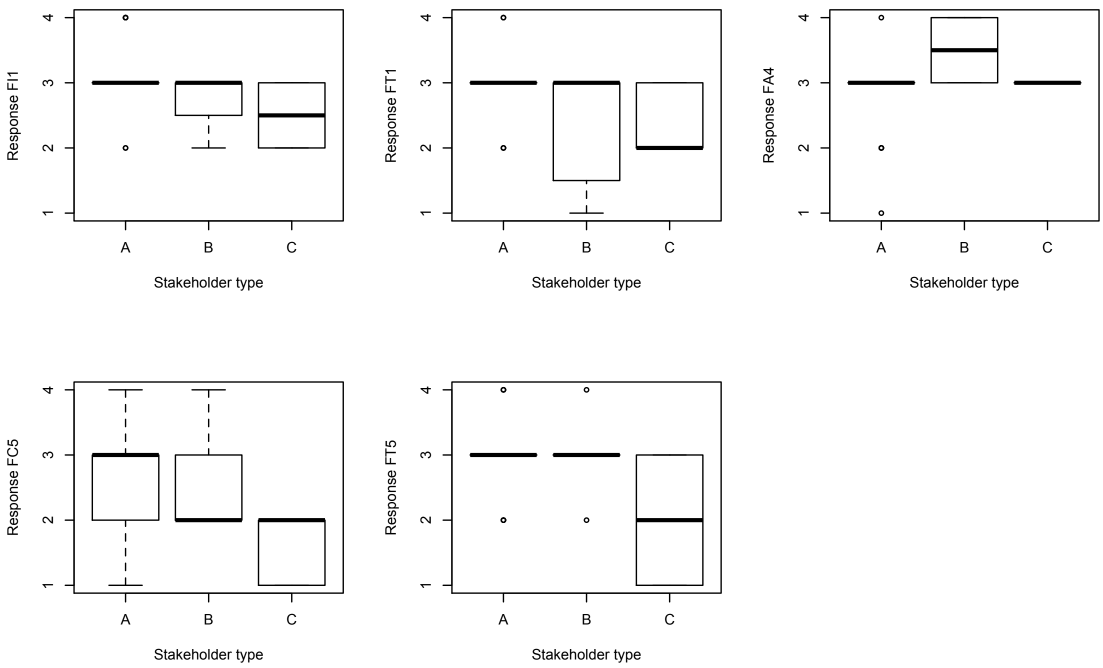


Figure 5.7 - Box plots of those feasibility factors where there were significant differences between stakeholder group responses. Plots show the mean response, standard error, interquartile range and outliers per stakeholder group (A – researchers, B – practitioners, C – policy makers).

Again there was little difference noted between stakeholder groups in assessing the feasibility of each action. From 48 feasibility factors scored across the 12 strategy groups, Figure 5.7 shows the five responses where stakeholder groups answered with significantly different responses. When participants were asked to score strategy 1 researchers (A) and policy makers (C) gave significantly different responses for the ease of implementation, with researchers 'Likely possible' and policy makers 'Likely not possible' (p=0.047, Figure 5.7: FI1). Also for strategy 1, researchers (A) and practitioners (B) gave significantly different responses for the capacity to sustain over time (p=0.035, Figure 5.7: FT1). When scoring the affordability of strategy 4 researchers and practitioners answered with significantly different responses with practitioners scoring more positively though all stakeholder groups responded positively (p=0.023, Figure 5.7: FA4). For strategy 5 researchers and policy makers gave significantly different responses for both institutional capacity and capacity to sustain over time (p=0.048, Figure 5.7: FC5; p=0.048, Figure 6.8: FT5).

5.3.3.3 – Adaptation at multiple scales

Respondents were asked to score both the spatial and temporal scales at which the adaptation strategies could be actioned. Figure 5.8 shows the mean results of this scoring process colour coded with the 'Feasibility' of the action as described. All of the 'Definitely Feasible' actions are scored towards the lower end of the temporal scale which is perhaps indicative that these strategies are already in place in some locations or already have demonstrated benefits (for example in 'Test catchments' e.g, Owen *et al.* 2012).

The spatial scale at which adaptation actions should be taking place shows a desire for management at the landscape scale. The majority of strategies are placed between 'In the catchment' and 'Regional/National' which connects with the increased engagement with the landscape scale concept in freshwater environmental management (Wagner *et al.* 2011; Koomen *et al.* 2012; Iverson *et al.* 2014; Schindler *et al.* 2014; Mazziotta *et al.* 2014; Bastian *et al.* 2014)

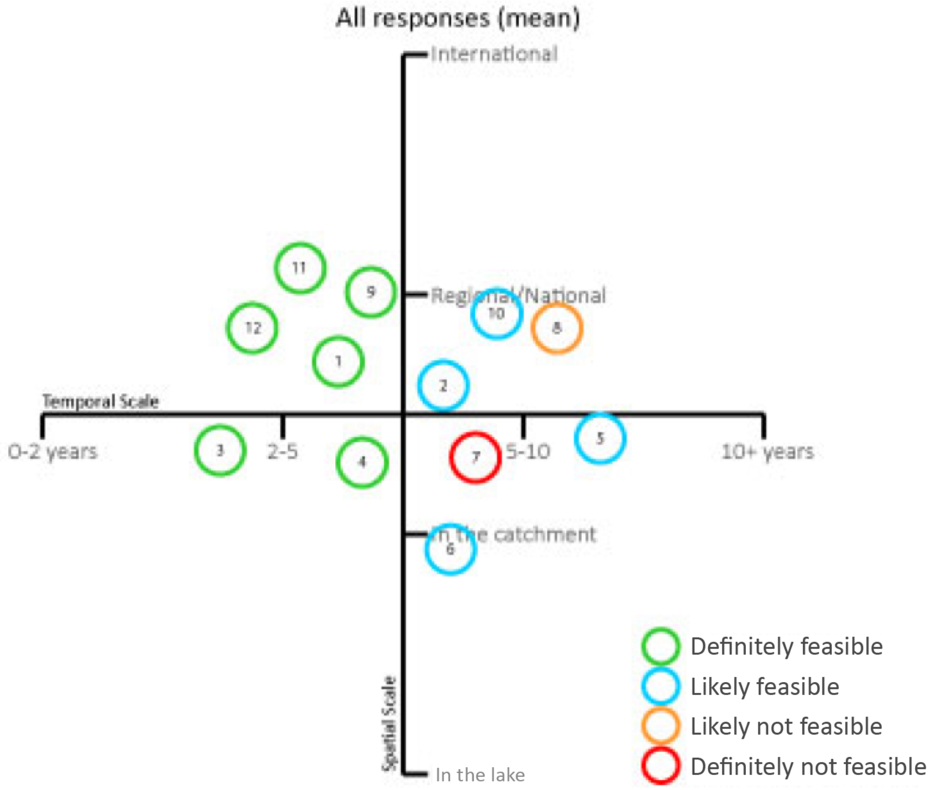


Figure 5.8 - Adaptation strategies plotted across multiple spatial and temporal scales, colour coded by strategy feasibility.

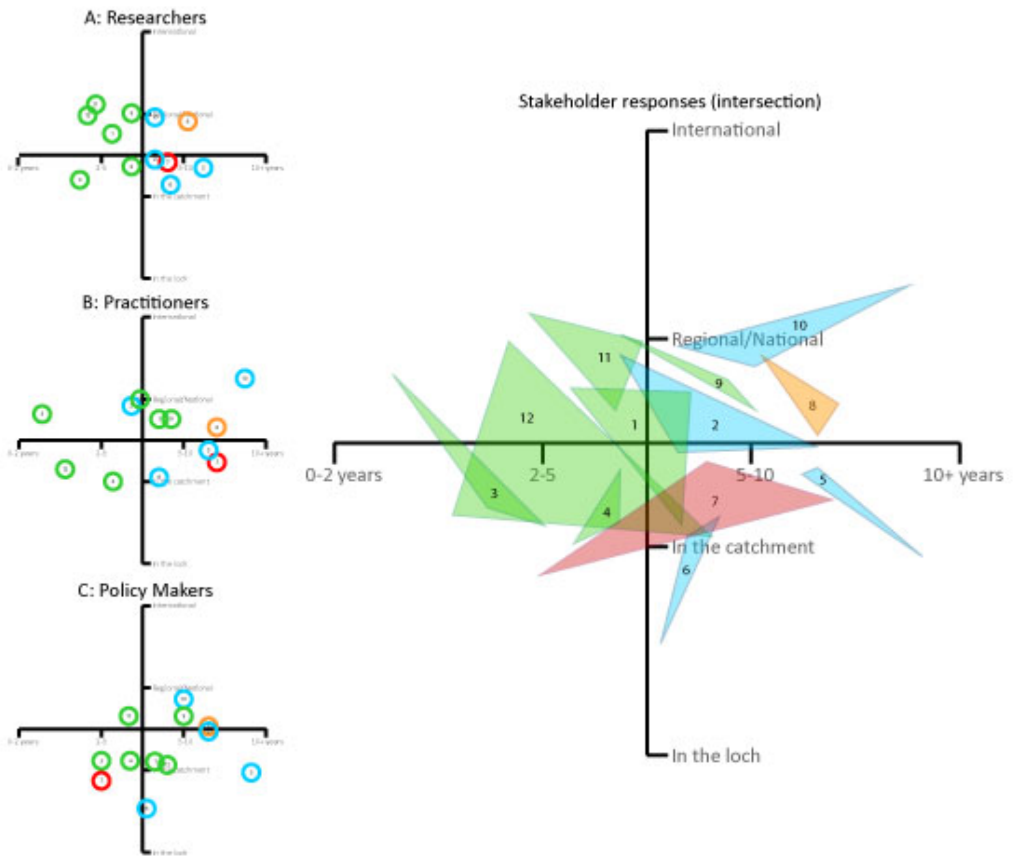


Figure 5.9 - Scale responses broken down by stakeholder group and a visual representation of the intersection and overlap of stakeholder responses where the smaller the strategy triangle the more coherent the response across stakeholders.

It is interesting to break these results down further to stakeholder level (see Figure 5.9) where there is a greater divergence of opinion than previously encountered. Practitioners use the widest range of temporal scales with strategy 3 (*Mitigate other threats including invasive species, habitat fragmentation and pollution*) placed within the 'We should be/are already doing this 0-2 years', and strategy 10 (*Fund more interdisciplinary research*) within the 'Long term aim 10+ years'. This potentially points to a disconnect between the early uptake of these actions already happening at the site and catchment scale by practitioners, who may feel that action is more important than further research.

5.3.4 Adaptation challenges

No matter how desirable an adaptation strategy may be, and how feasible and at what scale it has been identified to work at, there will undoubtedly be challenges applying these ideas and actions on the ground. In the final section of this survey participants were invited to discuss these challenges.

5.3.4.1 Knowledge gaps

Participants were asked: 'With particular reference to climate change adaptation, what are the key gaps in knowledge facing environmental managers?' The responses were coded and four main themes were identified.

1. Interaction between climate change and other pressures

Respondents are concerned that we currently do not have sufficient knowledge of other threats to our standing freshwaters, and particularly how those stressors will interact. It is a concern that, for example, direct climate changes, eutrophication, invasive species, changing catchment runoff and the re-mobilisation of contaminants will act synergistically to the detriment of freshwater habitats. Ecosystem changes in response to change will also be non-linear and it is difficult to untangle the interlinked effects of management actions and natural processes of change over time. It is unlikely that adaptation actions focused on one threat can mitigate all these pressures as there will likely be compounding or confounding effects. There was also concern that many of pressures will be site-specific and so tackling them with a single national scale adaptation strategy will likely not be sufficient.

2. Downscaling climate pressures to site level

Respondents were concerned that there was a lack of robust site level projections of climate change. This is further complicated by a perceived non-transferability of data (ecological, hydrological and climate) between sites, leading to uncertainty in the potential effects of climate change at the site level. There was further concern around the issue of changes to climate extremes in particular as hydrological changes causing fluctuations in water levels could have significant impacts to both social and ecological systems. While these concerns are undoubtedly valid, climate models are becoming more sophisticated, working at smaller spatial and shorter temporal scales, all the time. Hopefully work like that provided in Chapter 4 of this thesis will provide the level of local scale climate and ecohydrological modeling detail required to help focus action for conservation management.

3. Lack of long term, in depth, knowledge of species and system function

Many of the survey participants noted concerns surrounding the lack of knowledge of current species and particularly the current function of systems. While the large number of academic respondents may partially explain this, there is definitely a concern that we do not yet know enough about the physiology, life cycles and distributions of most species, in particular those non-enigmatic species which may be acutely important for system function. There is also uncertainty surrounding the potential of species to respond to change without intervention, either through phenotypic plasticity or locally evolved genetic adaptation to climate.

Many participants also responded that there is general lack of chemical and biological monitoring data specific to the Scottish resource. While there are over 25,000 lakes only around 400 are regularly monitored by SNH and SEPA through designated site condition monitoring and WFD related monitoring. This lack of long term data means understanding the results of adaptation interventions will be difficult to interpret and respond to.

Two particularly interesting areas of research potential were also raised in relation to current knowledge. Firstly, to what extent will lake functioning be maintained or disrupted, even though climate change may affect species composition and interactions? At what point will these changes become detrimental to system function, when will a previously resilient lake change form and function, and what is the tipping point? Secondly, what is the role of networks of undesignated lakes in supporting designated lakes and how can this be monitored and supported. While there is much focus on the effect of protected areas as radiating hubs or refuges from which species can recover and renew, how do non designated lakes contribute to this. This links to questions surrounding species movement more generally and how to promote movement of native species whilst controlling non-natives; how to prioritise species (and at the same time select species which will not be conserved, even if rare). These are pertinent questions for standing freshwaters where the habitat itself can be considered static and so movement between sites is particularly complex.

4. Lack of clear guidance to action

The final knowledge gap survey participants identified was an absence of accessible adaptation guidance from public bodies and regulators specific to adaptation for conservation objectives. Knowledge is also failing to be communicated from academic research to policy makers and practitioners regarding which adaptation actions are most important, which have the greatest financial return and over what time scale. Generally there is a feeling that currently there is insufficient scientific evidence to justify investment as we do not have sufficient knowledge of the climate impacts on lake function to know which adaptation actions will be most important to implement. This is also highlighted as a lack of knowledge surrounding how to address the social and institutional barriers to effectively move from the assessment of key vulnerabilities and identification of adaptation strategies into action, hopefully a key space that work like this thesis can begin to address.

5.3.4.2 Barriers to implementation

Participants were asked: ‘What are current barriers to implementation of adaptation actions for conservation?’ The responses were coded and four main themes were identified.

1. Political inaction

Respondents noted the lack of political will with, in particular, a short term focus making longer term adaptation actions particularly difficult to justify and fund. This was viewed as a non-commitment on the part of governments deeply rooted in a general malaise and inaction broadly on climate change at the international level.

This lack of political will, tied to uncertainty, short termism and the low political relevance of the environment, leads to very poor motivation for political actors to engage in adaptation. It was suggested that this may be due to environmental issues being a perceived barrier to economic growth or due to current legislative and institutional procedures at higher levels (e.g. EU WFD) being focused on short-term results now rather than building resilience for the future.

Survey participants were also concerned by the lack of common language across all areas of policy and legislation in relation to adaptation, leading to miscommunication and a lack of collaboration between agencies and stakeholders at all levels. This led to missed opportunities for integrated policies, due to 'silos' evident across research and management communities. This lack of a coordinated or cooperative approach is fuelled by a wide array of pressing political challenges and cross scale institutional barriers that make 'rational' adaptation strategies very difficult to implement.

2. Lack of finance

Lack of investment, resources and funding was highlighted by a large number of participants as a key challenge. 'Squeezed' budgets, even for tackling existing pressures, mean that adaptation is currently a 'bolt-on' where only 'win-win' management practices are even considered let alone actioned. Budgets for environmental monitoring are being cut and, because of the untested and broad nature of adaptation principles, funding for these ideas to date has been difficult. With the move to more direct adaptation strategies and actions hopefully this will become more realistic but funding is likely to remain a considerable challenge in the near future.

3. Current conservation focus

Interestingly, the current focus of conservation management was considered to be a key barrier to the implementation of adaptation strategies. The 'single species focus' from some quarters was highlighted as problematic as was the fixed and static (both spatial and temporal) nature of current protected areas. This was further linked to difficulty in integrating conservation actions into the management of the wider landscape matrix, particularly in urban areas but also in agricultural environments.

4. Communication

The final theme of current barriers to implementation was the lack of clear and transparent communication of research findings, which are needed to demonstrate impacts and motivate action. This may be due to restricted scientific findings stored behind journal paywalls, but could equally be due to the relatively immature nature of the subject. Having persuasive evidence that actions have a positive effect, and clearly communicating those findings widely using non-technical language, was seen as a priority and something that is not currently occurring. There was also considered to be a lack of clear communication around the most vulnerable lake types and species/habitats, which may be impeding actions as managers are uncertain where to act. This is coupled with a lack of message giving confidence that it is an issue that site managers should deal with. Furthermore there is a lack of clear procedures with basic guidance to support informed action by managers. This has led to a limited understanding by the general public and water managers of the value of wetland ecosystem services, the threat of climate change and the potential of possible management actions. This is clearly linked to the lack of guidance available, which was identified as a key knowledge gap and which must be addressed as a priority.

5.4 Discussion

The results presented here give an in depth investigation of the management potential of adaptation strategies for conservation. Data has been presented based on a survey of 40 individuals representing a wide array of organisations involved in the environmental management of standing freshwaters. For the first time both the desirability and feasibility of proposed adaptation strategies and actions have been outlined, helping us to prioritise action to reduce the vulnerability of Scotland's standing freshwaters to climate changes.

5.4.1 Adaptation perceptions

Following the growing cross sector acceptance of the need for climate change adaptation (Miller *et al.* 2012; Biagini *et al.* 2014; Ausden 2014), it is unsurprising that the survey respondents were overwhelmingly in favour of the need for climate change adaptation to be an integral part of conservation management for Scotland's standing freshwaters. The majority of respondents canvassed were broadly in agreement with the statements throughout (mean results in Figure 6.2) and the results highlighted that the survey participants were very well suited to task. It also indicated that the key terms used throughout this study are well known to conservation managers in Scotland suggesting that the need for adaptation policies and actions is already a part of the environmental management discourse in Scotland.

It would be interesting to ask a wider array of environmental managers – i.e. those not specifically interested in freshwater conservation – as it is likely some responses would be very different. While the overall desire for climate change adaptation may be broadly accepted, the significance of the standing freshwater resource in particular may well be viewed differently by those either dealing across all habitat types or with specialisms in other areas (Adger *et al.* 2005; Hofmann *et al.* 2011; Lemieux & Scott 2011).

There was very little statistically significant difference between the responses of the different stakeholder groups throughout the survey. While this could be due to the power of the sample sizes or the grouping selection, it can also be viewed as a positive indication of coherent views between potentially disparate groups involved in managing the Scottish freshwater resource. This is a positive indication for coherent management moving forward, where consistency across all scales will be needed to achieve positive outcomes (Brooks *et al.* 2006; Sievanen *et al.* 2012; Pooley *et al.* 2014; Whitehead *et al.* 2014).

5.4.2 Adaptation strategies

The need for adaptation strategies and actions beyond broad principles has been well documented (Wilby *et al.* 2010; Hall & Murphy 2011; Mawdsley 2011; Game *et al.* 2011). To date progress towards this goal has been limited and difficult to achieve with so much variety of system form and function. For environmental managers to have the best chance of actually making progress with managing uncertain futures, having clear guidance is key (Heller & Zavaleta 2009; Cross *et al.* 2012a; Fabricius & Cundill 2014).

Table 5.13 combines the desirability and feasibility scores, which allows us to investigate the issue of priority in conservation management. Clearly those strategies which are considered most desirable and definitely feasible should be considered the priority (Rowland *et al.* 2011; Lemieux & Scott 2011). In this case those strategies are 3 (mitigate other pressures), 4 (create ecosystem based catchment management plans), 11 (implement a new management culture) and 12 (adopt long term approaches, increasing education). These adaptation strategies span spatial and temporal scales from immediate actions within the lake to long term actions at the national scale. Having a wide array of strategies with associated specific actions will be key to achieving conservation success (Cook *et al.* 2012).

Table 5.13 - Adaptation strategy showing the overall scoring for both feasibility and desirability of the strategy.

Adaptation Strategy	Desirability	Feasibility
1 - Implement a full scale protected area system review	**Very Desirable**	**Definitely Feasible**
2 - Practise proactive intensive species management to secure priority populations	**Very Desirable**	**Likely Feasible**
3 - Mitigate other threats including invasive species, habitat fragmentation and pollution	**Most Desirable**	**Definitely Feasible**
4 - Create ecosystem based catchment management plans for all of Scotland's freshwater systems	**Most Desirable**	**Definitely Feasible**
5 - Create a new, lake specific, protected area network	**Desirable**	**Likely Feasible**
6 - Manage reserves for complex, non-linear, changes and 'landscape asynchrony'	**Very Desirable**	**Likely Feasible**
7 - Invest in ecosystem based catchment restoration	**Desirable**	**Definitely Not Feasible**
8 - Establish an ecological lake network in Scotland	**Desirable**	**Likely Not Feasible**
9 - Re-assess current conservation goals	**Desirable**	**Definitely Feasible**
10 - Fund more (interdisciplinary) research	**Very Desirable**	**Likely Feasible**
11 - Harness a new environmental management culture with climate change adaptation at its core	**Most Desirable**	**Definitely Feasible**
12 - Adopt long term and regional perspective in planning, modelling and management	**Most Desirable**	**Definitely Feasible**

Grouping together actions into broad adaptation strategies was necessary to allow survey participants to respond within a reasonable time. Unfortunately this approach meant that contradictory or very diverse actions could be included within a single strategy. This led to participants in some cases struggling to score the single groupings, which may explain the central tendency we see in the scoring (for example see Figure 5.8). It was hoped and expected to see a wider range of responses across both spatial and temporal scales (as in Muir *et al.* 2012, Moss 2014a) and if more specific actions rather than strategy groups had been scored this could have provided finer scale.

Scoring actions across temporal and spatial scales does give a clear indication as to the priority of action however. There were strategies which provided coherent response between participant groups (see Figure 5.9) – in particular strategies 3 (mitigate other threats including invasive species, habitat fragmentation and pollution) and 4 (create ecosystem based catchment management plans for all of Scotland's freshwater systems) were consistently scored between groups as being actionable in the short-medium term. Given that these strategies were also scored as most desirable and definitely feasible they should be the starting point for management.

5.4.3 Adaptation challenges

With any change in the focus and priority of environmental management there will undoubtedly be challenges and barriers to implementation. While the adaptation strategies presented here were all considered desirable and many considered feasible, participants still felt that there was an array of challenges including concerns surrounding knowledge gaps (Interaction between climate change and other pressures; Downscaling climate pressures to site level; Lack of long term, in depth, knowledge of species and system function; Lack of clear guidance to action) and barriers to implementation (Political inaction; Lack of finance; Current conservation focus; Communication). It is also likely that these barriers will be different in different places and at different scales, which makes the task of producing coherent policy very difficult (Rahel 2007; Nielsen & Reenberg 2010; Mastrangelo *et al.* 2013).

These challenges are not unique to Scotland nor to standing freshwaters however (Nel *et al.* 2009; Sievanen *et al.* 2012; Berger *et al.* 2014). Cross sectoral challenges have been widely acknowledged (c.f Harrison *et al.* 2015), with funding for environmental management limited there is a continued need to act without full knowledge, making use of the best available understanding and experience. In Scotland particular challenges may include the perceived cost of re-naturalising waterbodies as opposed to that funding being spent on hard infrastructure flood defences (Iacob *et al.* 2014), or on the inability of environmental organisations to challenge agricultural practises backed by large financial lobbies (Thornton *et al.* 2014). The political context within the UK at present is deeply uncertain, with 'austerity' funding cuts and the withdrawl of the EU dominating headlines and policy agendas alike. Within this context it seems unlikely that environmental concerns will be given the space and funding necessary to overcome these challenges.

It is easy to read all the challenges and become depressed or disillusioned as to the possibilities adaptation strategies and actions offer for the future. It is important to remember that the adaptation strategies were received overwhelmingly positively with all 12 strategies being considered desirable and 10 of 12 being scored feasible or very feasible. This gives a strong basis of action at the landscape scale to reduce the sensitivity of our standing freshwater systems by increasing both the system resilience to change but, primarily, by increasing the adaptive capacity of the system to give best chance of continued function of our lake systems providing the ecosystem services upon which we rely.

Adaptation management requires a proactive approach tackling management at multiple spatial and temporal scales (Heller & Zavaleta 2009; Glick *et al.* 2011b; Khamis *et al.* 2014). While there may be win-win solutions in the short term that tackle current issues and reduce system sensitivity to future change, we also need to open discussion around more challenging, longer term management options (Parr *et al.* 2003; Davies *et al.* 2014). There will be and are major challenges, and there will be opposition, but without considering the wide array of options we cannot hope to manage our standing freshwaters to remain fully functioning parts of our natural heritage. We can become too caught up in challenges, knowledge gaps or uncertainty and these can develop themselves into barriers to effective adaptation causing potential delay or withdrawal (Lemieux & Scott 2011). The results presented here show that there is clear desire for action and we must do our best to communicate this knowledge as widely, and as clearly, as possible.

5.5 Summary

A multipart online survey was carried out with 40 participants actively involved in freshwater environmental management. Participants came from a wide array of organisations representing three broad stakeholder groups: researchers, practitioners and policy makers. Perceptions of adaptation were common across stakeholder groups, with all respondents agreeing with the climate change threat and need for adaptation strategies as a response. The majority of participants also disagreed that we know enough about the composition and function of Scotland's standing freshwaters.

For the first time a long list of over 85 adaptation actions specifically applicable to Scotland's standing freshwaters has been collated. The actions were grouped into 12 adaptation strategies. All adaptation strategies were considered desirable which is testament to the increasing importance of the term, the forefront of the climate change agenda in environmental work and understanding of the threats increasing over the coming century.

Six strategies were considered 'Definitely feasible' with a further four considered 'Feasible'. This provides us with a wealth of potential actions that could help to reduce system sensitivity by increasing adaptive capacity or system resilience. Each adaptation strategy was mapped across spatial and temporal scales. This produced the greatest difference of opinion between the stakeholder groups potentially indicating that practitioners are already implementing some of these actions.

With any change in the focus and priority of environmental management, there will undoubtedly be challenges and barriers to implementation. While the adaptation strategies presented here were all desirable and the majority feasible, participants still felt that the main challenges lay at the feet of politicians willing to engage with long term changes rather than short term deliverables - and thus funding for landscape scale management and research is lacking. Funding was identified as the major barrier to implementation, but a number of participants also highlighted a lack of knowledge. While there are undoubtedly challenges to the success of adaptation actions it is likely that without attempting to move the static management narrative forward we will not succeed and our natural environment will be altered beyond restoration. There is little doubt that this must be an adaptive process – closely monitored and regularly reviewed, with changing baselines incorporated into a more fluid understanding of what is natural given changing environmental conditions. The adaptation strategies discussed here must be used as a strong starting point to invigorate the discussion at a national level with clear guidance provided to site managers on the range of threats and potential actions.

Chapter 6 – Discussion & Recommendations

6.1 Guiding adaptation actions

Given the magnitude of projected climate changes and the struggle to agree on and then meet mitigation targets, it is unsurprising that the topic of climate change adaptation has become increasingly common and of increasing policy interest (Burch *et al.* 2014; Brown *et al.* 2015). Across the globe the issues affecting our environment have become mainstream news with a daily barrage of media tales of destruction increasing pressure on politicians to act (Vogel *et al.* 2007; Meinard & Quétier 2014; Pooley *et al.* 2014). The issues are extremely complex, however, with no simple option, panacea or silver bullet. Instead this is a convoluted web of social, political, economic and environmental issues with numerous actors and stakeholders at every level from the single individual to global treaties encompassing hundreds of nations and billions of people (Bates *et al.* 2008; Cundill *et al.* 2012; Martin *et al.* 2012; Agard *et al.* 2014; Pooley *et al.* 2014; Brown *et al.* 2015).

Adaptation has become the key term where we have been unable to reach consensus on limiting human impact. Instead of mitigating change society must adapt to it, and we must make changes to our governance structures in order to adapt the environment to change of unprecedented speed and magnitude (Bainbridge *et al.* 2011; Hill & Engle 2013). The IPCC AR5 (Agard *et al.* 2014) defines adaptation as something that "changes the fundamental attributes of a system in response to climate and its effects." The authors go further than in previous reports to propose a clear distinction between *autonomous, incremental* and *transformational* adaptation. Autonomous adaptation occurs when management that would have occurred anyway has a broader impact on increasing resilience to change. Incremental adaptation describes much of what is already occurring and planned in the environmental management space: actions where the central aim is to maintain the essence and integrity of a current system or process at a given scale. Transformational adaptation, however, goes beyond this to look at processes which are more difficult to implement, which would require major investment and which are potentially higher risk. This might include the introduction of new technologies or practices, the formation of new structures or systems of governance, or shifts in the location of activities (Kates *et al.* 2012).

We can assume that transformational adaptation will have life-altering consequences because it is systemic and results from a shift in paradigms and values (Folke *et al.* 2010). But there are questions here about the realities of systemic change and how the consequences may be managed across different sections of society with differential vulnerability to climate change impacts. In transformation, as in climate change more broadly, there are likely to be both successful and unsuccessful actions. However, transformation as a concept has the potential to facilitate more effective adaptation than incremental adaptation (Kates *et al.* 2012; Park *et al.* 2012). In order to fund, implement, measure and prove transformation in adaptation, funders, practitioners and researchers will need incentives to work over longer time horizons on interventions that have bigger impacts (Bassett & Fogelman 2013). However, longer term change is more difficult to track and monitor and in many cases more difficult to implement given the short term cyclical nature of political systems (Kates *et al*. 2012). A further challenge is adaptation practitioners and funders have not yet clearly specified what counts as 'transformative', which poses a major challenge to facilitating transformational adaptation (O'Brien 2012). At what scale, spatially and temporally, does an action have to take place to be transformative? It is likely that transformational actions will be long-term, if not irreversible, but how long is long enough and how do we measure the value and impact of different actions (Park *et al*. 2012)? There is a major issue with how policy makers can marry their short term political ambitions with longer term societal responsibility (Kates *et al.* 2012). It is likely that any such change would be met with large scale opposition given the complex web of actors operating across sectors.

Climate changes will impact across every aspect of our environment and society, every habitat and species (European Environment Agency 2012; Harrison *et al.* 2015). The changes will happen over time and autonomous and incremental adaptation, if properly targeted, will allow us to keep pace with some of these changes (Moran & Alexander 2014; Ausden 2014). To truly adapt however more complex and difficult transformational decisions will have to be implemented. This will need strong leadership at the national scale to implement holistic and large-scale adaptation (Mazziotta *et al.* 2014). No matter whether actions are autonomous, incremental or transformational there can be no doubt that action is needed (Ausden 2014; Moss 2014). To allow this to happen we need to target actions built upon a solid evidence base (Sutherland *et al.* 2010).

6.2 Targeting action: focus

There is huge debate surrounding the focus and scale of conservation actions globally, particularly as climate change exerts increased pressure on conservation management systems, which are already struggling with numerous pressures (Dudgeon *et al.* 2006; Crossman *et al.* 2012; Berry *et al.* 2013; Whitman *et al.* 2013).

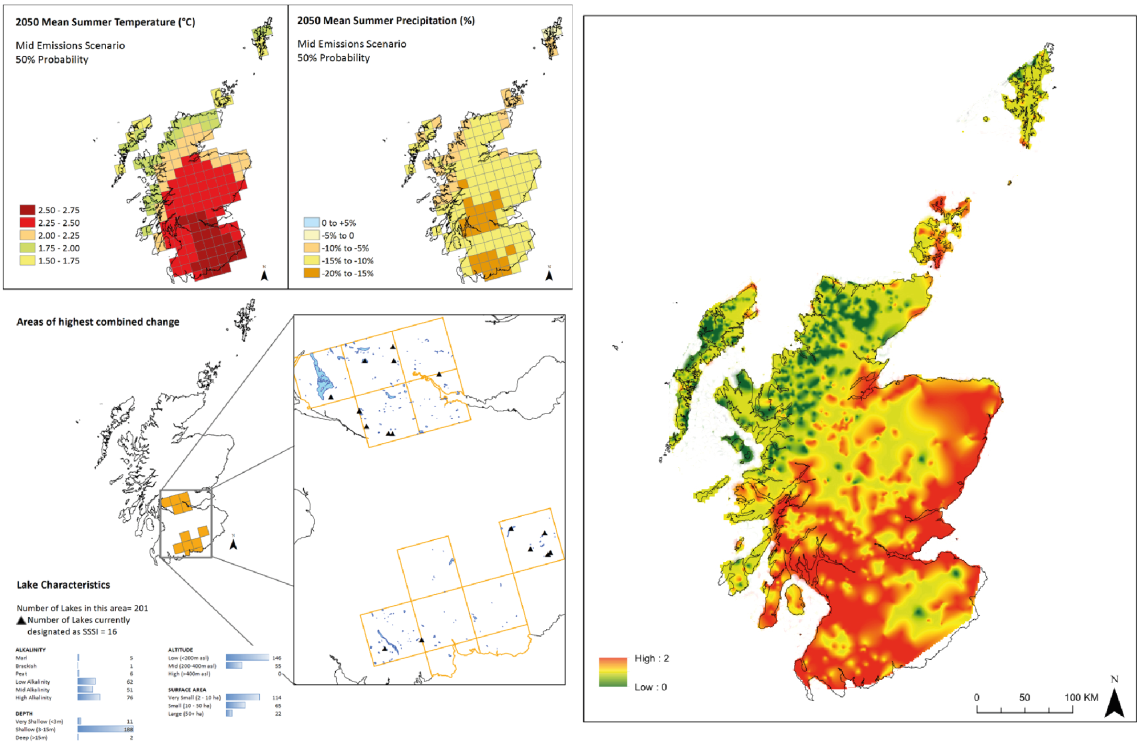


Figure 6.1 - Adaptation actions should be targeted to those areas of greatest change (left; Figure 3.13) and highest vulnerability (right; Figure 4.10)

We can use the results of climate modeling and vulnerability analysis to focus spatial action in Scotland. Climate models, discussed in detail in Chapter 3, clearly show the scale and impact of the challenge in Scotland. By highlighting those areas of highest projected change we can best target action to the highest-risk areas. Similarly, we can use climate models to feed into vulnerability analysis (Chapter 4) and map the resulting lake vulnerability across the country. Figure 6.1 shows outputs of both these analyses. In the first instance adaptation strategies and actions should target lakes in the highlighted areas, primarily in southern and central Scotland. By managing those most vulnerable systems first lessons can be learnt for management of less vulnerable systems, budgets can be prioritized for those actions that work, and a body of evidence built up to support further action across the country.

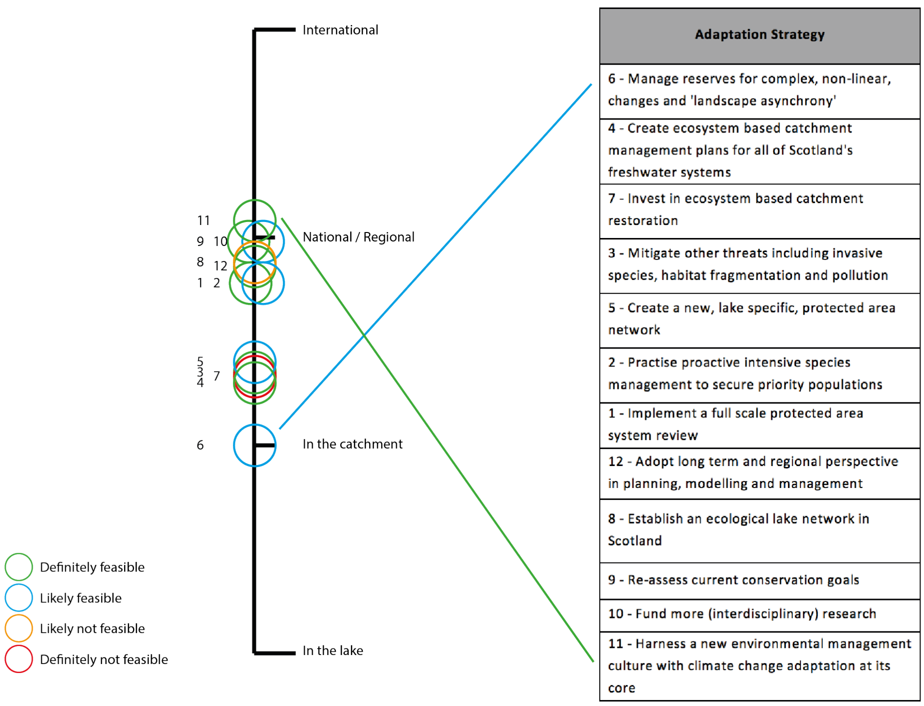


Figure 6.2 – Focus of adaptation strategies based on the scale of action from within the lake to international scale policy

Adaptation strategies themselves must also work at different spatial scales, and the focus of action will depend on the specific strategy and resulting actions. Figure 6.2 elaborates on the analysis presented in Chapter 5.3.3 by plotting each strategy only along the spatial scale access. This highlights the number of strategies which are likely to need enacting at the national/regional scale, perhaps indicating a desire from the stakeholders to see strong policy led by national organisations such as the Scottish Government, Scottish Natural Heritage and the Scottish Environment Protection Agency.

6.3 Targeting action: priority

Much of the climate change adaptation literature and guiding principles highlight the need for holistic, landscape-scale conservation policy (Schwenk & Donovan 2011; Lemieux & Scott 2011; Mazziotta *et al.* 2014). As discussed in Chapter 2, lakes are a perfect example of the need for larger scale actions (Adrian *et al.* 2009). It is unlikely that singular species management will be a feasible strategy going forward given climate change pressures and threats including invasive non-native species (Scott *et al.* 2012; Harrison *et al.* 2014). While there may be potential in some cases for very local-scale water body management, in all cases a wider catchment approach will be desirable (Moss 2014). Lakes are embedded in a wider landscape and their health relies heavily on the associated land use in the surrounding catchment (Zhang *et al.* 2001; Dessel *et al.* 2008; Weijters *et al.* 2009; Maberly & Elliot 2012). Adaptation strategies will only be successful when seen within this context (Dudgeon *et al.* 2006; Soranno *et al.* 2009).

The reality of action though is more complex of course: the priority of which strategies can be acted upon, where and when will depend on a variety of factors including political will and funding. It will also depend on the timescale over which strategies can be implemented to best effect. Figure 6.3 outlines the spatial scale of actions which could be directly implemented as a timeline for action. It is of interest that all of those strategies scored ‘Definitely Feasible’ are those which were prioritised as being actionable in the short-medium term. These strategies should be prioritised for implementation.

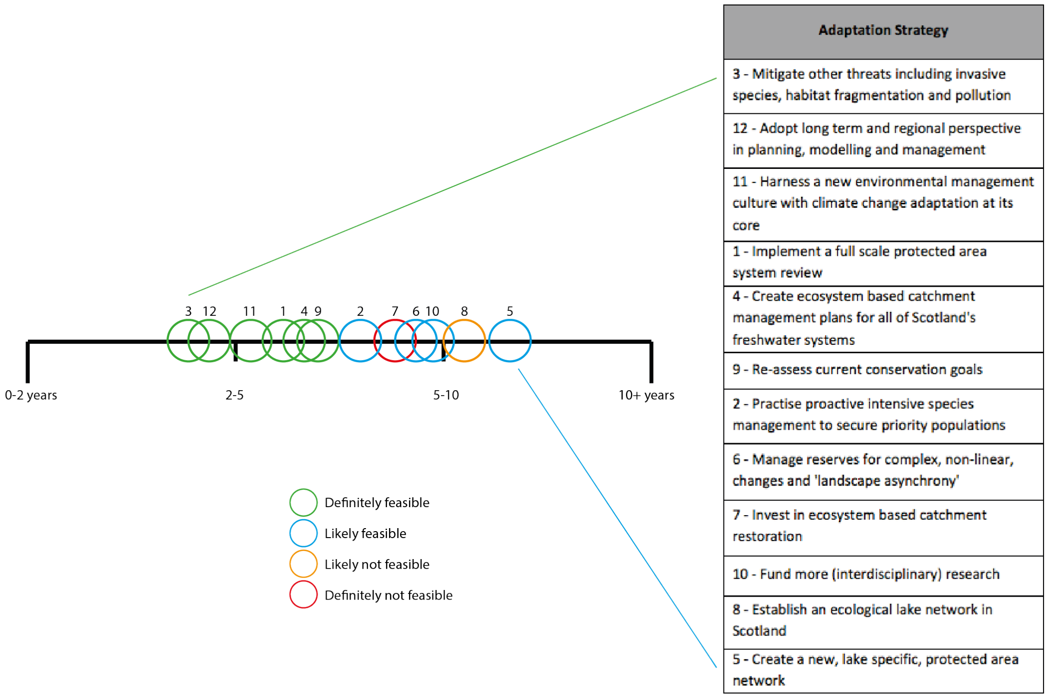


Figure 6.3 - Prioritising action on a temporal scale from 0-2 years to 10+ years.

6.4 Targeting action: reducing vulnerability

The overarching aim of adaptation strategies must be to reduce the vulnerability of systems to change, allowing the most ‘natural’ future possible. Vulnerability, as described in this thesis, is the combination of external exposure and internal sensitivity, defined in terms of resilience (physical features) and adaptive capacity. To reduce vulnerability therefore requires strategies targeted to these components. While mitigation measures could potentially reduce exposure the reality is that significant change is unlikely, even with recent political measures such as the Paris Treaty which looks likely to be ratified in 2017. System sensitivity, as described here, is the combination of adaptive capacity and resilience. While it may be possible to make some changes to improve the resilience of a specific site (for example digging deep water areas, changing average depth) it is unlikely to be a widespread action as the necessary infrastructure cost and unknown effects of such action make it prohibitive. Therefore, management actions which can really have an effect in reducing system vulnerability must target those elements which combine to make up the adaptive capacity of that system, namely the current condition of the water body, ecology, catchment intensity or wildness. Management interventions must target those elements which can by definition be managed. While rewilding could be a possibility at a national scale, this would have to be significant and cross sectoral to influence the wildness component of the adaptive capacity score. The reality is that the best chance for strategies to improve the adaptive capacity of Scotland's lake systems is going to focus around improving the quality of the catchment and water body. Figure 6.4 shows how each adaptation strategy could impact on the component adaptive capacity scores.

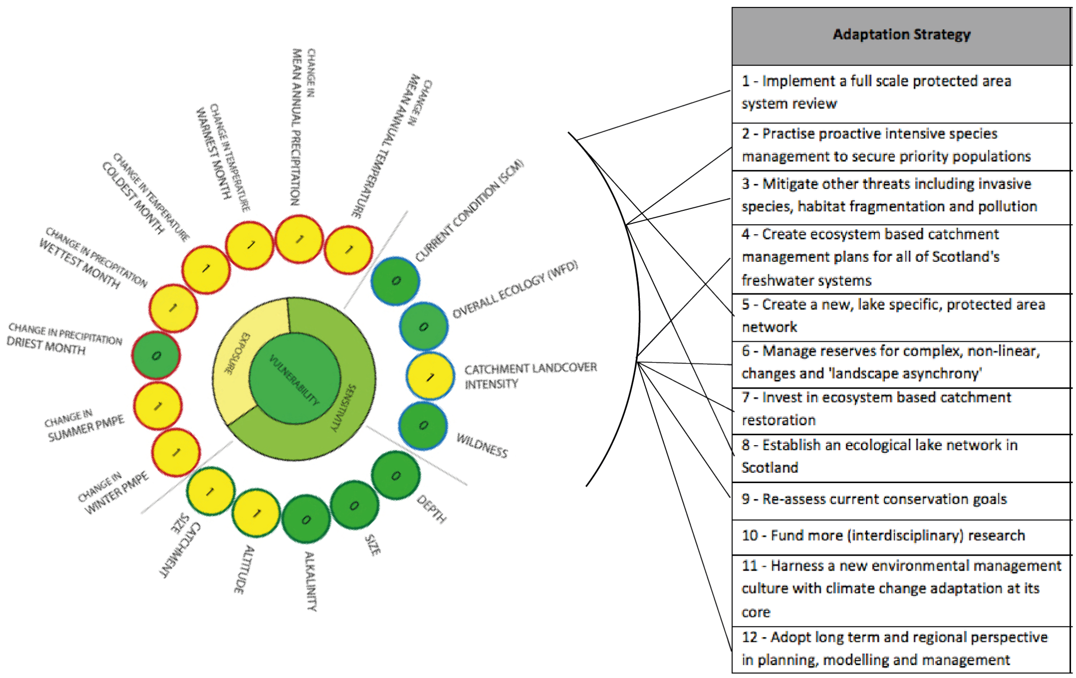


Figure 6.4 - Strategies which could improve the adaptive capacity, and therefore vulnerability of lake systems in Scotland

The major tool for conservation management is the establishment of protected areas. There are global targets for growth of protected areas across all biomes and protected areas are likely to be an important component of adaptation strategies in the near future (Hameed *et al.* 2013). For standing freshwaters as with other ecosystems, we currently focus much effort on conserving the baseline through management of protected areas, such as SSSIs, as discussed in Chapter 2. These areas will likely remain priorities; however, in the face of changing environmental conditions, as seen in Chapter 3, we may need to review this focus on protected area boundaries and, in addition, shift away from designations based on species composition to more inclusive habitat-level functional designations.

Strategies 1, 5, 6, 8 and 9 all directly relate to this area, improving the representation and ecological integrity of Scotland's protected area system. Monitoring current protected areas, expanding areas and even the establishment of new areas are incremental adaptation options, and are an important first commitment for policy makers. Some have argued that instead of more protected areas we need to better manage those areas we currently have (Fuller *et al.* 2010). As an adaptation tool, however, these areas will need to become more flexible spaces, with moving boundaries depending on the season or species (Hameed *et al.* 2013; Kati *et al.* 2014; Thomas & Gillingham 2015). However, that will require transformation of legislation at a national or international scale. It will need a management body which is flexible to react to short term extremes with the necessary powers to move protected area boundaries, potentially in conflict with other users (Miller *et al.* 2012).

Strategies 2,3,4,6, and 7 all aim to improving the quality and adaptive capacity of catchments at a larger scale across the country. The importance of reducing sources of harm not linked to climate change as a first action is central to achieving successful adaptation. For lakes, which are intrinsically linked with their surrounding landscapes, the key is the lake landscape connectivity, and through this applying appropriate, focused management at the catchment scale. This means taking practical measures to reduce both point and diffuse pollutants: actions like fencing off or planting buffer strips along lake margins have been shown to be effective in reducing levels of phosphates and nitrates in the water (Hoffman et al. 2009). Catchment-scale management can again be effective for freshwaters when attempting to 'renaturalise' watercourses to enhance resilience. Among examples of such work in the UK, Tweed Forum have used such an approach (Gilvear *et al.* 2013).

Working closely with land owners and other organisations throughout the catchment, they have coordinated an approach leading to the fencing off and planting of many kilometres of river and the control of cattle access to watercourses, enabling regeneration of bankside vegetation and re-establishment of more natural channel processes over significant lengths. They have succeeded through working with land owners across the catchment to control and effectively eradicate the alien invasive Giant Hogweed (*Heracleum mantegazzianu)*, which had threatened to dominate the whole water environment. Tweed Forum have been working with local farmers in the Cheviots on an initiative to adapt to and build resilience against climate change through pro-active development of individual farm plans. Taken together such initiatives lay the foundation to create and sustain high-quality, multi-use and resilient landscapes.

Establishing ecological networks for standing freshwaters is a more challenging strategy because each lake is essentially an isolated body, a fragment within the wider landscape. Particularly for sensitive sedentary species, human interactions to facilitate the movement of species between these fragments should be considered. There is a major need to minimise catchment pressures to promote minimally altered runoff and nutrient fluxes to maintain the natural ecological continuum. However, there are both up and downstream connections, and many mobile or migratory species travel between lake systems and further investigation of above and below ground links between catchments should be encouraged. Assisted migrations have been trialed for some alpine species (Rahel & Olden 2008; Hagerman *et al.* 2010a) and translocations of priority fish species have already occurred in the UK (Lyle & Maitland 2011). The recent publication of the SNH Species Translocation guidelines (NSRF 2014) are a clear indication that this is a priority for environmental management more broadly and should be welcomed. All actions need to be executed making use of the best possible scientific analyses and the ESVRA framework, as presented in this thesis, can provide a robust approach to further studies be they on habitats, species or at a larger landscape scale. Where data are available, spatial risk analysis, such as the one carried out here, combined with species and habitat envelope modelling, will be particularly important in attempting to future-proof current management decisions.

Strategies 10, 11 and 12 (Figure 6.4) speak more broadly to building institutional capacity to make climate change adaptation a central component of all actions across sectors. Whilst this will not specifically act to increase adaptive capacity of lake systems these strategies will strengthen the movement, bring climate change adaptation to the centre of all environmental management decisions at a national scale.

6.5 Adaptation challenges ahead

With any change in the focus and priority of environmental management there will undoubtedly be challenges and barriers to implementation. While the adaptation strategies presented in Chapter 5 were all considered desirable and many considered feasible, there remain an array of challenges including concerns surrounding knowledge gaps (Interaction between climate change and other pressures; downscaling climate pressures to site level; lack of long term, in depth, knowledge of species and system function; lack of clear guidance to action) and barriers to implementation (political inaction; lack of finance; current conservation focus; communication). It is also likely that these barriers will be different in different places and at different scales, which makes the task of producing coherent policy very difficult (Rahel 2007; Nielsen & Reenberg 2010; Mastrangelo *et al.* 2013).

The evidence base surrounding the complex interactions between biotic and abiotic elements of ecosystems is weak, and given the lack of quantified experimental or modelled data there are great difficulties moving forward into uncertain futures which are very likely to include much greater system stressors (Hallegatte 2009; Jackson 2011; Rowan *et al.* 2012; Carter & White 2012).

These challenges are not unique to Scotland nor to standing freshwaters (Nel *et al.* 2009; Sievanen *et al.* 2012; Berger *et al.* 2014). Cross sectoral challenges have been widely acknowledged (c.f. Harrison *et al.* 2015), with funding for environmental management limited there is a continued need to act without full knowledge, making use of the best available understanding and experience. In Scotland particular challenges may include the perceived cost of re-naturalising waterbodies as opposed to that funding being spent on hard infrastructure flood defences (Iacob *et al.* 2014), or on the inability of environmental organisations to challenge agricultural practises backed by large financial lobbies (Thornton *et al.* 2014). The political context within the UK at present is deeply uncertain, with 'austerity' funding cuts and the withdrawl of the EU dominating headlines and policy agendas alike. Within this context it seems unlikely that environmental concerns will be given the space and funding necessary to overcome these challenges.

More effective dialogue is needed between biodiversity science, policy and public to overcome such issues and underpin the sustainable use and conservation of biodiversity (Meinard & Quétier 2014). Many initiatives exist to improve communication, but these largely conform to a linear or technocratic model of communication in which scientific 'facts' are transmitted directly to policy advisers to 'solve' problems (Dana *et al.* 2012; Cook *et al.* 2013). While knowledge exchange programmes are increasing, as seen in Chapter 5, there continues to be a divide between academia, policy and society (Martin *et al.* 2012; Glass *et al.* 2013). Better use of digital technologies can start to bridge this divide but communications professionals must be engaged for greatest success (Meinard & Quétier 2014).

The strategies described here give a strong basis of action at the landscape scale to reduce the sensitivity of our standing freshwater systems primarily by increasing the adaptive capacity of the system to give best chance of continued function of our lake systems providing the ecosystem services upon which we rely. Adaptation management requires a proactive approach tackling management at multiple spatial and temporal scales (Heller & Zavaleta 2009; Glick *et al.* 2011b; Khamis *et al.* 2014). While there may be win-win solutions in the short term that tackle current issues and reduce system sensitivity to future change, we also need to open discussion around more challenging, longer-term management options (Parr *et al.* 2003; Davies *et al.* 2014). There will be and are major challenges, and there will be opposition, but without considering the wide array of options we cannot hope to manage our standing freshwaters to remain fully functioning parts of our natural heritage. The results presented here show that there is clear desire for action and we must do our best to communicate this knowledge as widely, and as clearly, as possible.

6.6 Future research recommendations

In order to continue, support and strengthen the development of adaptation strategies and resulting actions for Scotland's standing freshwaters in the face of a changing climate, future research should focus on:

- Increased research into connectivity of standing freshwaters, particularly north-south across the country and how this could be better understood to form ecological networks. This should include increases in monitoring of lake systems, particularly more small waterbodies, in those areas identified as being most vulnerable to change.
- Investigation into legal mechanisms for different types of protected areas, such as floating, movable and seasonal protected areas, and how these would be identified, managed and policed.
- Investment in country wide catchment management plans, ideally at lake catchment scale, though more realistically for major rivers catchments to start.
- Funding links between science and digital communications agencies. Utilising the potential to engage in creative storytelling and visualising data to increase public understanding and public support for transformational policy change.

6.7 Summary

Climate changes will impact across every aspect of our environment and society, every habitat and species. The changes will happen over multiple spatial and temporal scales, with the reality of scale of impacts across all sectors still unknown.

Adaptation will require a range of autonomous, incremental and more difficult transformational decisions to be implemented. This will need strong leadership at the national scale to implement holistic and large-scale adaptation. There can be no doubt that action is needed and this action needs to be built upon a solid evidence base.

This thesis has increased knowledge of lake resource in Scotland including clear presentation of numbers, density and physical characteristics. This comprehensive GIS can be also integrated with other datasets if they become available to help environmental managers consolidate information to make the best possible decisions.

The results of climate modelling show clear patterns of global change to temperature and precipitation and the projected impacts downscaled to Scotland and to individual lakes. While all models include levels of uncertainty, the scale and rate of projected changes are unprecedented. As models improve in spatial and temporal resolution (i.e. modelled to changes over months or seasons at tens of metres) the quality will improve for specific sites. However, the current level of detail presented should be sufficient for adaptation planning to start now.

The vulnerability assessment is a major challenge due to the numerous ways of conceptualising vulnerability. It is unlikely there will ever be a single model solution. Incorporating elements of the resilience of physical characteristics of the lake into the analysis leads to a more robust analysis of vulnerability than previously possible. The model presented here is intended to be transparent and simple to use to allow end users to make best use of the results. While this model can help start a dialogue, it is, on its own, insufficient, as decision taking is complex, iterative and often selective in the information used. In many ways the large scale vulnerability mapping may be the most useful output for highlighting areas of vulnerability at a broad scale rather than site specific issues.

For the first time over 85 adaptation actions relevant to Scotland’s standing freshwaters have been revealed. Clustered into 12 adaptation strategies clearly linked to broad guiding adaptation principles for biodiversity conservation, these have been explored in terms of both desirability and, crucially, feasibility. It is likely that those strategies identified as most desirable and most feasible will be those which are already happening (such as environmental education programmes) or where there are few barriers to entry (for example, expanding current protected areas) – in essence autonomous or incremental adaptation options. These must continue to be a priority. Interestingly there is clear desire from the respondents to engage with some of the more transformational policies too, particularly larger scale more holistic approaches. The feasibility of these issues (in particular Strategy 7: Reconnecting Catchments) highlights issues with funding and political issues which are exactly the challenges policy needs to overcome to be truly transformational.

In conclusion, while there are undoubtedly challenges ahead for Scotland's standing freshwaters and for those who manage them, there is clear opportunity to make proactive and engaged decisions to minimise the impact of climate changes on the conservation interest of these important habitats.

Appendix A - Muir et al, 2012

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Climate change and standing freshwaters: informing adaptation strategies for conservation at multiple scales

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Climate change will have a major impact on freshwater environments globally. The management of these ecosystems is one of the key challenges currently facing environmental policymakers and producing well-informed climate change adaptation strategies is a priority. Links between climate, hydrology and ecology are poorly understood, and relatively little study has taken place on conservation of standing freshwaters, particularly with respect to landscape context and connectivity in a changing environment. Scotland's lakes (termed lochs in Scotland) contain more than 90% of Great Britain's total freshwater resource. They are distributed across the country, occurring in a wide variety of types and sizes, together providing habitats of international importance for numerous species. There is a pressing need across all geographic scales to conserve these environments in the face of changing water body, catchment and global pressures, including climate change in particular. Here, we introduce a new conceptual framework (ESVRA), designed to inform climate change adaptation strategies for standing freshwaters at multiple spatial and temporal scales. Adaptation actions will be contingent on the nature and scale of the climate changes, the sensitivity of different lake types to change and the resilience of the specific conservation interests involved. As such, potential adaptation actions are situated within current debates in conservation management surrounding priority species and habitats, threats from multiple stressors, invasive non-native species and the potential benefits of catchment-scale management. Following the ESVRA framework, we present an analysis of climate projections for Scotland; discuss potential climate impacts on the physico-chemical, hydromorphological and ecological processes within lakes; offer a spatial risk assessment for the conservation of Scottish lakes; and advance the adaptation discussion, moving from broad adaptation principles to specific adaptation actions protecting the conservation interests of individual lakes.

Key words: *Scotland, climate change, adaptation, conservation, freshwater, lake*

Introduction

Global climate change is predicted to be a major cause of change across all ecosystems and there are particular concerns about impacts on freshwater systems due to the coupling of direct impacts on both hydrology and ecology (Bates *et al.* 2008; Wilby *et al.* 2010). Predicting how standing freshwater systems, and ecological interests in particular, will respond to climate-driven changes greatly amplifies uncertainties already implicit in their environmental management. Subsequently, this increases the challenge of developing adaptation strategies and management targets for species and habitats of conservation priority (Kernan *et al.* 2010).

A range of methods have been utilised to protect freshwater habitats and species, including legislation, economic instruments, campaigning, research and site designation (see Heller and Zavaleta 2009). Whatever the balance of actions, projected changes in climate present a new set of challenges with potential impacts across the standing water resource base (Adrian *et al.* 2009). In this context, there is a need to review how we plan to protect the conservation interests of freshwater sites. This is especially important in the face of other changing lake and catchment pressures – which include diffuse pollutants, morphological modification, recreation and invasive species (Maltby *et al.* 2011). In the UK the implementation of the EU Water Framework Directive (WFD; European Commission 2000) has prompted renewed interest in standing freshwaters and ecological quality.

Scotland, a relatively small (*c.*79 000 km^2), maritime state on the Atlantic margins of North Western Europe, provides a good example of the challenges faced by those wishing to develop adaptation strategies. With over 25 000 lakes and ponds with surface areas greater than 0.1 ha (Hughes *et al.* 2004), standing freshwaters are an iconic part of Scotland's landscape, and represent over 90% of the freshwater resource of Great Britain (Lyle and Smith 1994). The many different forms and sizes of lakes contribute outstanding geodiversity, as well as habitats of international importance for numerous species of conservation interest (SNH 2003). This variety, and the particular catchment and landscape settings within which these lakes are situated, provide added challenges for conservation management. As elsewhere, there is little comprehensive data covering the ecology of all these water bodies, or the bio-physical processes that support ecosystem functioning, with particular gaps in knowledge relating to the distribution of physical types, current conditions and the legacy of historical impacts on biodiversity patterns and trends (Rowan *et al.* 2012).

The aim of this paper is to provide a conceptual framework to inform climate change adaptation strategies and conservation targets for standing freshwaters using, as an example, Scotland's lake resource. This framework is based on an understanding of the complexities of climate projections and resultant hydrological and ecological changes. Whilst this study has its origins in Scotland, the framework should be applicable to freshwater management across Europe and beyond.

The ESVRA framework for adaptation management

We present a conceptual framework (Figure 1) to assist policymakers and practitioners in adaptation planning. We suggest that practical actions should be identified by working through the framework's four key stages:

- understanding exposure to the pressure (external drivers);
- considering the sensitivity of the system at multiple scales (internal functions);
- exploring areas of vulnerability and risk (a measure of sensitivity plus exposure); and
- consideration of multiple possible responses.

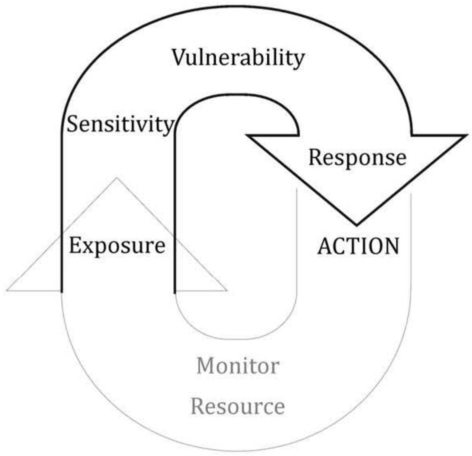

Figure 1 The ESVRA Framework for adaptation management showing the four stages (Exposure, Sensitivity, Vulnerability and Response) that should be assessed in order to create well-informed adaptation actions

Here, we use each of the elements of the framework in turn to explore adaptation strategies to minimise the impacts of climate change on the conservation interest of Scotland's standing freshwaters.

Exposure: climate change projections for Scotland

Mooij *et al.* (2005) stress the importance of having reliable models of climate change at a scale that is relevant to management strategies and actions. In this respect, Scotland is well served, with the launch in 2009 of the latest United Kingdom Climate Projections (UKCP09 2011). Based on the Hadley MET Office HadRM3 regional climate model, UKCP09 provides projections at a finer spatial and temporal resolution than ever before. UKCP09 allows output related to three greenhouse gas emissions scenarios, developed from the IPCC Special Report on Emissions Scenarios – high (SRES A1FI), medium (SRES A1B) and low (SRES B1). More significantly, UKCP09 quantifies the uncertainty associated with each projection by assigning each outcome a related probability, or likelihood of occurrence (Street *et al.* 2009).

Figure 2 shows one set of data output from the UKCP09 model. Incorporating these data into ARCGIS 10, it is

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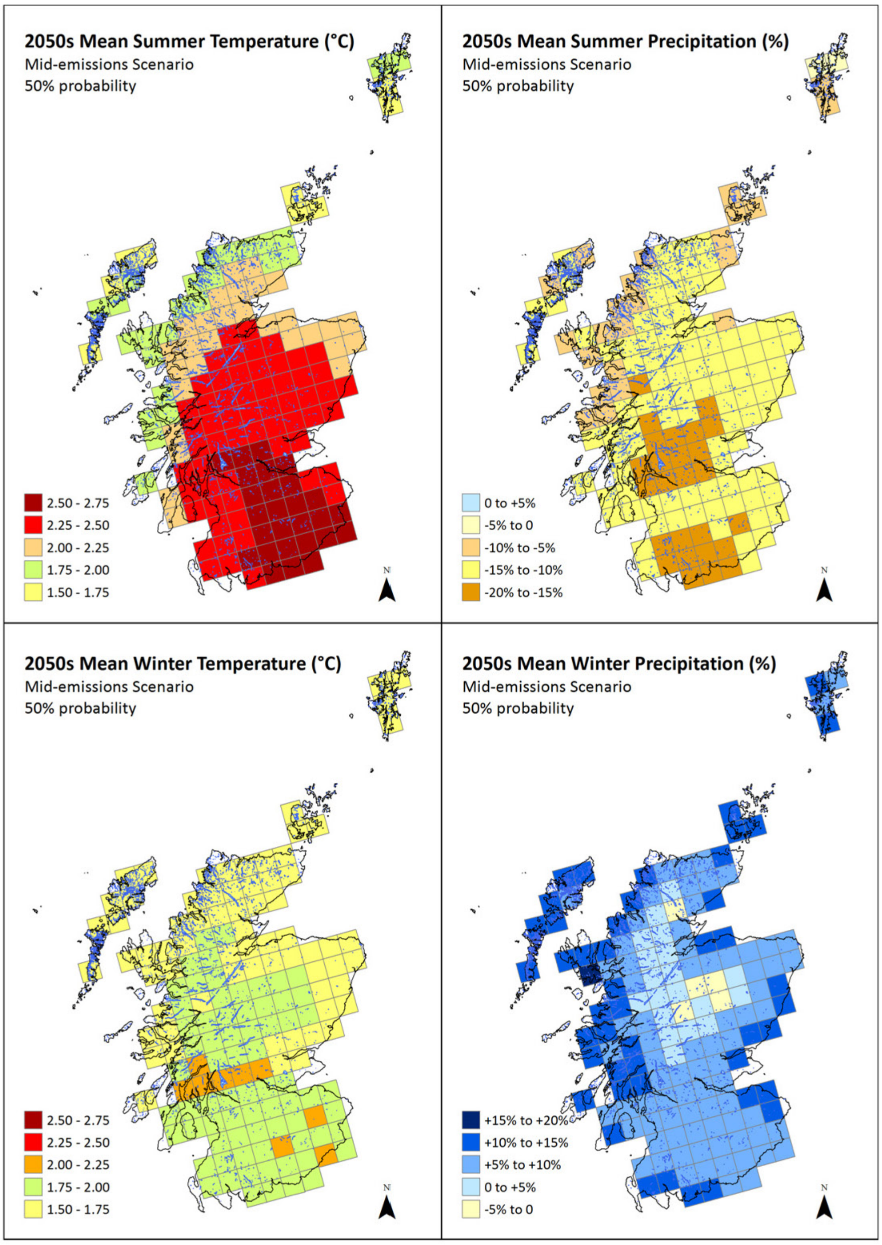

Figure 2 **Projected changes to mean summer and winter temperatures and precipitation are illustrated for Scotland in the 2050s, based on a 50% probability and mid-emissions scenario**
Source: Data from UKCP09 analysed in ARCGIS 10

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possible to map the spatial distribution of projected changes across Scotland. At this scale, patterns indicate a South East/North West gradient across Scotland. Whilst most of the country faces warmer annual mean temperatures, with wetter winters and drier summers, there are some areas, such as the Cairngorms (central highlands), that are projected to face drying throughout the year.

We can further analyse projections against baseline data to show more specific changes at the catchment scale. An example of such data is provided in Figure 3. Temperature and rainfall projections from UKCP09 are plotted against METOffice baseline data. Potential evapotranspiration (PET), an important factor affecting catchment water balance, is calculated using the Hamon method (McCabe and Wolock 2002). Changes of this magnitude are likely to greatly affect the functional hydrology and ecology of standing freshwater systems.

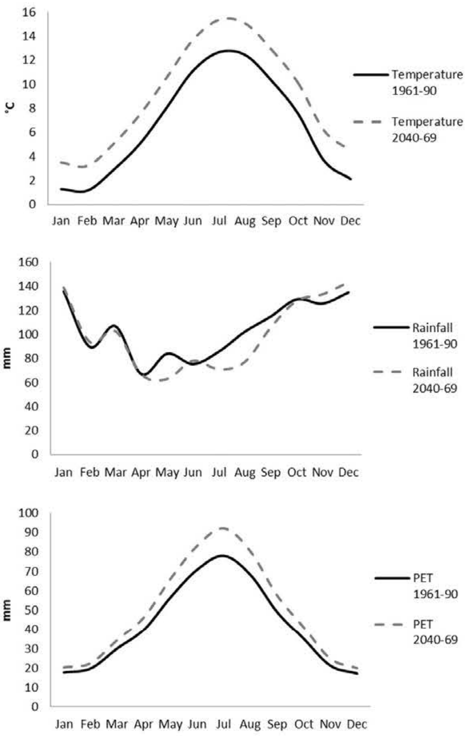

Figure 3 Kingside Loch – a small (6.4 ha surface area) mid altitude (348 m asl) lake in the Scottish Borders, designated as a Site of Special Scientific Interest (oligotrophic loch)
Note: Graphs show projected changes to average monthly air temperature (°C), rainfall (mm) and potential evapotranspiration (mm) from MET Office baseline period data (1961–90; solid line) to UKCP09 2050s (2040–69) projection (50% probability mid emissions scenario (dashed line)

Sensitivity: climate change impacts on lake hydrology and ecology

Climate change is likely to affect the hydrological cycle most significantly through altered temperature and precipitation patterns, intensities and extremes (Kundzewicz *et al.* 2007). This will impact the ecology of standing freshwaters through multiple pathways, acting at different geographical scales and in response to landscape setting. The concept of the scaling relationships between lakes and their surrounding environment, the lake landscape-context (Soranno *et al.* 2009), provides a way of approaching the relative sensitivity or resilience of an individual lake to change.

Small shallow lakes situated within a large catchment (characteristic of South East Scotland) are likely to respond differently to large deep lakes (typical of North West Scotland). The former may be sensitive to reduced summer precipitation, with lower runoff reducing the flushing of the system and increasing residence times. This may lead to greater accumulation of phosphorus in sediments (as shown by Spears *et al.* (2012) for Loch Leven) which, when periodically released from storage can cause cyanobacterial blooms (Elliot 2010; Carvalho *et al.* 2011). By contrast, a large deep lake is less likely to respond to these drivers of change, but may be more sensitive to other changes; for example, longer periods of thermal stratification reaching greater depth can lead to deoxygenation of the hypolimnion and stressed fish assemblages (Arvola *et al.* 2010). The importance of the lake landscape-context also extends to lakes with similar intrinsic characteristics (e.g. surface area, mean depth, alkalinity) but different catchment characteristics (size, vegetation cover or land use), that will likely respond differently to change (Webster *et al.* 1996; Galbraith and Burns 2007).

Here, we group expected changes into three functional categories: those affecting physico-chemical (broadly water quality), hydromorphological (physical structure and habitat) and biological elements of the lake system (see Table 1). There are problems with attributing changes solely to climate, because lake systems are commonly affected by multiple interacting stressors. In Scotland, for example, other key stressors include water-level management for hydropower generation, land-use management – with intensive farming practices leading to eutrophication – and acidification from atmospheric deposition of industrially-derived emissions (Bennion *et al.* 2001; Maltby *et al.* 2011). These, and similar issues, are themselves subject to other drivers including EU Common

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Table 1 Expected impact of climate changes to physico-chemical, hydromorphological and biological functioning of standing freshwaters

Physico-chemical changes Water temperature; mixing/stratification; dissolved oxygen; carbon flux; nutrient loading; alkalinity/acidity; photic environment	Expected physico-chemical changes will include increased water temperatures (particularly in the epilimnion), including less frequent ice-cover and earlier snowmelts (Bates *et al.* 2008). Related consequences include earlier onset and longer periods of thermal stratification, potentially modifying dissolved oxygen and carbon levels, as well as increasing the release of sediment-bound nutrients and contaminants into the water column. These changes to water chemistry may lead to increases in cyanobacterial blooms, for example, which will alter the photic environment and ecological function of the whole system (see Carvalho *et al.* 2011).
Hydromorphological changes Hydrological regime (amount and timing of flow); retention time; sediment changes; shoreline complexity; connectivity; habitat structure	Changes in precipitation amounts and timings, resulting in more extreme floods and droughts, will alter surface and groundwater flows. Variability is likely to increase, affecting hydraulic retention times as well as sediment transport and nutrient loading. Changes to the water-level regime (Wantzen *et al.* 2008) will have consequences for lake–landscape connectivity and will result in changes to shoreline complexity and habitat structure.
Biological changes Productivity; phenology; trophic structure; species composition; invasive non-natives	Interactions between climate change and lake biology are complex because other factors such as stochastic phenology, resource availability, density dependence and predation may control the abundance, distribution and size of the biota (Adrian *et al.* 2009). Furthermore, these factors will operate at different geographical and temporal scales. Responses are often species-specific and vary between sites. Freshwater systems have already been shown to be undergoing changes in composition, organism abundance and productivity, and considerable evidence is already available showing phenological shifts in relation to earlier season warming potentially leading to trophic asynchrony (Winder and Schindler 2004; Dijkstra *et al.* 2011). Species ranges are documented to be changing, with species 'climate envelopes' (the geographic ranges with conditions suitable for species survival) (Dawson *et al.* 2003) showing latitudinal moves North and South, or up altitudinal gradients depending on thermal proclivity (Thomas *et al.* 2006).

Agricultural Policy reforms and carbon emission controls (Bates *et al.* 2008).

In addition to direct effects on habitat quality, climate change will lead to various indirect impacts. For example, it could enable greater movement of species (both native and invasive non-natives) altering competitive dominance, increasing predation rates and enhancing the virulence of disease (Rahel and Olden 2008). This can irredeemably alter system function, paving the way for further changes and increasing uncertainty with potential 'invasion pathways' through the landscape (Hellmann *et al.* 2008). Depending on local circumstances, management practices could range from complete eradication to tolerance and even consideration of the 'new' species as part of a 'novel community' – an enrichment of local biodiversity or a key element in maintaining or developing ecosystem services (Walther *et al.* 2009). Indeed, welcoming the arrival of 'new' or moving species may be an important adaptation strategy.

In terms of conservation sensitivity, priority habitats and species of conservation concern are recognised globally (e.g. IUCN Red Data Lists) and nationally (e.g. the UK Biodiversity Action Plan). Within Scotland, further guidance comes from the Scottish Biodiversity Strategy and SNH Species Action Framework. Figure 4 shows those lakes that are protected as designated Sites of Special Scientific Interest (SSSI) – based on freshwater species or communities of conservation value. A further 974 lakes fall within SSSIs designated for other biotic or geological features. While a number of sites also lie within other protected areas, the primary designation is as an SSSI. This shows 21 per cent (1079/5167) of Scotland's lakes are being actively managed for conservation, although only 2 per cent (105/5167) are protected primarily for their freshwater interests. This is perhaps indicative of imbalance between conservation based on species composition and that based on habitat designations or function.

A feature of many lake ecosystems is their relative isolation, with a resulting tendency towards endemism. Priority species in Scotland's lakes unsurprisingly include a number of fish such as Vendace (*Coregonus albula*), Powan (*Coregonus lavaretus*) and Arctic Charr (*Salvelinus alpinus*) (Adams *et al.* 2007; Graham and Harrod 2009). These are relict populations that colonised rapidly after the last glacial maximum (*c.*12 000 years ago). Much of their conservation interest derives from their subsequent biogeographic isolation, producing considerable variation in morphology, trophic ecology and life histories. Such

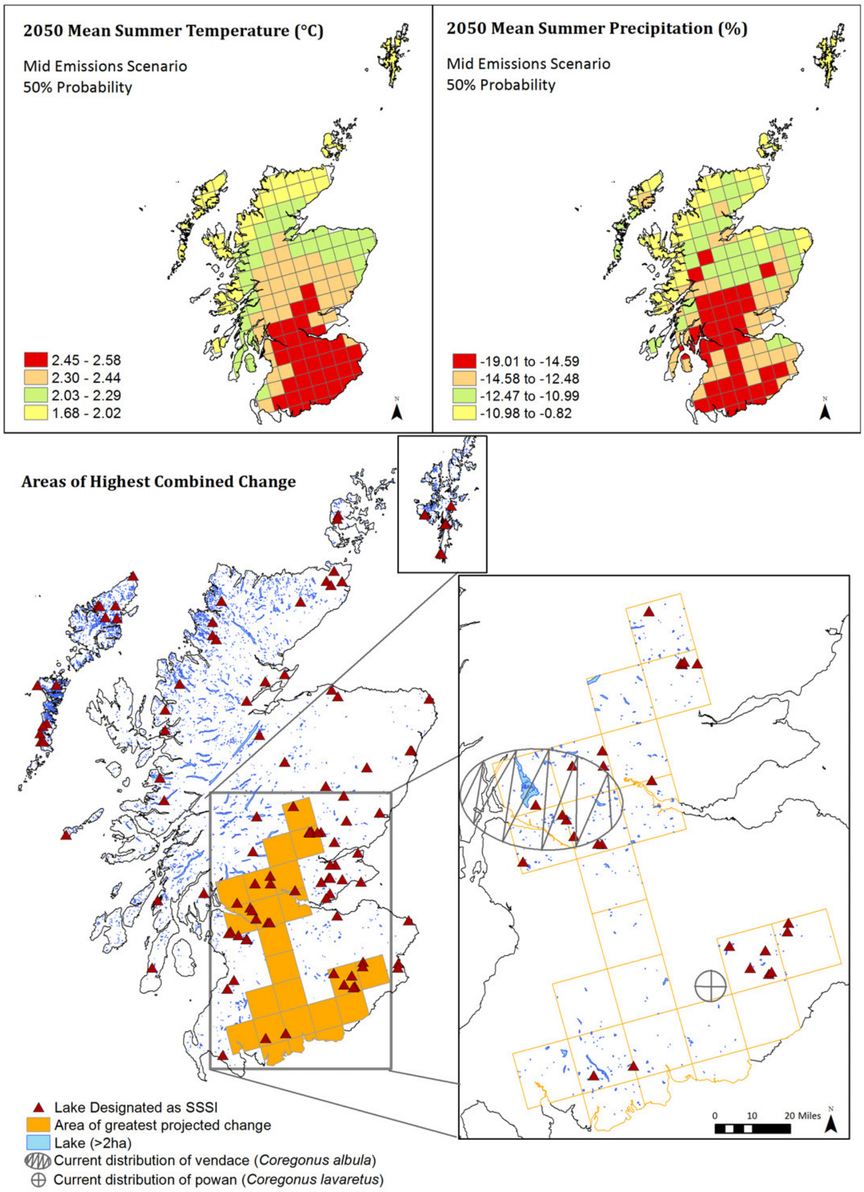

Figure 4 Spatial risk analysis for Scotland's standing freshwaters

Note: Mapping intersection of those areas projected to experience the greatest change to both mean summer temperature and mean summer precipitation (UKCP09 2050s, mid emissions scenario, 50% probability). Current distributions of two high-priority fish species are also highlighted

Source: Data from UKCP09, SNH and SEPA analysed in ARCGIS 10 species are particularly vulnerable to climate-forced changes due to low tolerance of changes in water temperature and resultant changes in dissolved oxygen – with the obvious implication that alterations to key water quality and habitat dynamics may lead to local and, ultimately total, extinction in Scotland (Lyle and Maitland 2011).

In contrast, for highly mobile species, such as wetland birds, many standing waters are themselves part of networks, or flyways, the connectivity of which is vital. In such a situation, understanding the usage of a particular lake at key seasons by different populations of resident and migratory wildfowl is essential to prioritising conservation actions (Boere *et al*. 2006). Within Scotland, for example, a large number of migratory waterfowl utilise lakes at various life stages and for various means, including foraging, roosting and breeding, and the use of the lake itself is often linked to other features of the local landscape in which it sits.

In between the extremes of the sedentary, isolated fish populations and the mobile, connected bird populations sit the vast array of other species, which must also be addressed in any comprehensive adaptation strategy. Within Scotland such species include Great Crested Newt (*Triturus cristatus*) and Common Toad (*Bufo bufo*), both of which utilise standing waters (though often small ponds) for breeding and are easily affected by toxins, eutrophication and habitat disturbance. A number of macrophyte species are also of high conservation concern, including Slender naiad (*Najas flexillis*), Shetland pondweed (*Potamogeton rutilus*) and Pillwort (*Pilularia globulifera*). Climate change effects on macroinvertebrates are still poorly known, particularly where they interact with other phenomena or stressors (Durance and Ormerod 2007). However, it is likely that any effects on macrophyte and macroinvertebrate composition or density will have a subsequent effect throughout the entire system. This is an area of major uncertainty and consequently we need better understandings of dispersal ability and sensitivity to change for these key structural elements in our freshwater systems.

Vulnerability: approaching a spatial risk analysis for Scottish lakes

Whereas we have used exposure to refer to external character, magnitude and rate of change, we have used sensitivity to reflect innate characteristics of a species or system. Vulnerability to climate change, as the term is used here, is the meeting of these two factors – sensitive systems or species likely to face extremes of climate changes will be most at risk and most vulnerable (Glick *et al*. 2011). Using GIS techniques one can start to map where areas of highest projected temperature and precipitation changes (or other relevant climate variables) coincide. Where known, one can also include data on the distribution of species or habitats of conservation concern and interest, or which we believe to be most sensitive to climate-induced change.

Using data from Scotland, Figure 4 outlines an attempt to map risk areas. We intersect those areas in the upper quartile of projected change in mean summer temperature and mean summer precipitation. The characteristics of those lakes within this area are outlined in Table 2. Of particular note here are 'marl' and 'high alkalinity' lakes because 20 per cent and 22 per cent respectively of the national resource fall within the high-risk zone. It is also interesting to note the high percentages of impacted lakes (with 'poor' or 'bad' WFD 'overall status') already within this zone. Given that climate change impacts will likely exacerbate current pressures, management of these lakes will continue to be a major challenge.

This of course does not mean other lakes are not at risk, but simply that this is the area of greatest change. Here, the aim is to prioritise those areas of highest risk to focus early conservation action. Included in Figure 4, for example, is the current range of two fish species of high conservation priority. Where known, distributions of other species or habitats of conservation concern could easily be added. Other climate projection scenarios could also be incorporated. We need further research on what the impacts of these changes will be across lakes with different physical forms and different landscape connections, and to the tolerances of priority species.

Response: multiple adaptation futures

Dependent on the underlying philosophy of environmental managers, the political will and timescale in which decisions can be made and funding put in place, there are many possible adaptation options. Figure 5 shows one conceptualisation of these futures – ranging from a scenario where we do nothing to an acceptance of predicted future conditions. The likelihood is that as pressures continue to rise, management actions will move from left to right along the continuum. The evidence provided thus far establishes that doing nothing is not a viable option. Given current paradigms in environmental management, we believe that in the first instance management of freshwater should make use of low-regret, evidence-based adaptation techniques, which are consistent with the contextual position of the lake in the landscape and with reducing other anthropogenic pressures at the catchment scale.

Table 3 outlines a series of adaptation principles for conservation, which offer a broad outline to guide future management decisions (Hopkins *et al*. 2007). A number of recent reviews (see Clarke 2009; Wilby *et al*. 2010) have welcomed these principles but call for a greater discussion of practical actions. For standing freshwaters,

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Table 2 Summary characteristics of Scotland's standing water resource highlighting the number of lakes which fall within the projected 2050 high risk zone (see Figure 4) and (b) Current WFD overall status for Scottish lakes subject to routine monitoring highlighting the number of lakes which fall within the projected 2050 high risk zone (see Figure 4)

	Total Resource	2050 high-risk zone	% of category
Lake Characteristic	**N = 5167**	**N = 388**	
Surface area			
Very Small (2–10 ha)	3624	239	7
Small (10–50 ha)	1205	107	9
Large (50+ ha)	338	42	12
Mean depth			
Very Shallow (<3 m)	225	24	11
Shallow (3–15 m)	4878	359	7
Deep (>15 m)	64	5	8
Altitude			
Low altitude (<200 m asl)	3664	249	7
Mid altitude (200–800 m asl)	1492	139	9
High altitude (800 m+ asl)	11	0	0
Alkalinity			
Marl	54	11	20
Brackish	36	2	6
Peat	737	9	1
Low Alkalinity	2407	126	5
Mid Alkalinity	1278	96	8
High Alkalinity	655	144	22
WFD 'Overall status' class	**N = 340**	**N = 43**	
High	61	0	0
Good / Good Ecological Potential	150	9	6
Moderate / Moderate Ecological Potential	68	15	22
Poor / Poor Ecological Potential	43	14	33
Bad / Bad Ecological Potential	18	5	28

as with other ecosystems, we currently focus much effort on conserving the baseline through management of protected areas (Table 3 – principle 1) such as SSSIs as discussed. These areas will likely remain priorities; however, in the face of changing environmental conditions we may need to review this focus on protected area boundaries and, in addition, shift away from designations based on species composition to more inclusive habitat-level functional designations.

The importance of reducing sources of harm not linked to climate change (Table 3 – principle 2) as a first action is, we believe, central to achieving successful adaptation. For lakes, which are intrinsically linked with their surrounding landscapes, the key is the lake landscape connectivity, and through this applying appropriate, focused management at the catchment scale. This means taking practical measures to reduce both point and diffuse pollutants – actions like fencing off or planting buffer strips along lake margins have been shown to be effective in reducing levels of phosphates and nitrates in the water (Hoffman *et al.* 2009). Catchment-scale management can again be effective for freshwaters when attempting to 're-naturalise' watercourses to enhance resilience (Table 3 – principle 3). Among examples of such work in the UK, Tweed Forum have used such an approach (see www.tweedforum.org). Working closely with land owners and other organisations throughout the catchment, they have coordinated an approach leading to the fencing off and planting of many kilometres of river and the control of cattle access to watercourses, thus enabling regeneration of bankside vegetation and re-establishment of more natural channel processes over significant lengths. They have succeeded through working with all relevant land owners across the catchment to control and effectively eradicate the alien invasive Giant Hogweed, which had threatened to dominate the whole water environment. And they have been working with local farmers in the Cheviots on an initiative to adapt to and build resilience against climate change through pro-active development of individual farm plans. Taken together such initiatives lay the foundation to create and sustain high-quality, multi-use and resilient landscapes.

Establishing ecological networks for standing freshwaters (Table 3 – principle 4) is a more challenging

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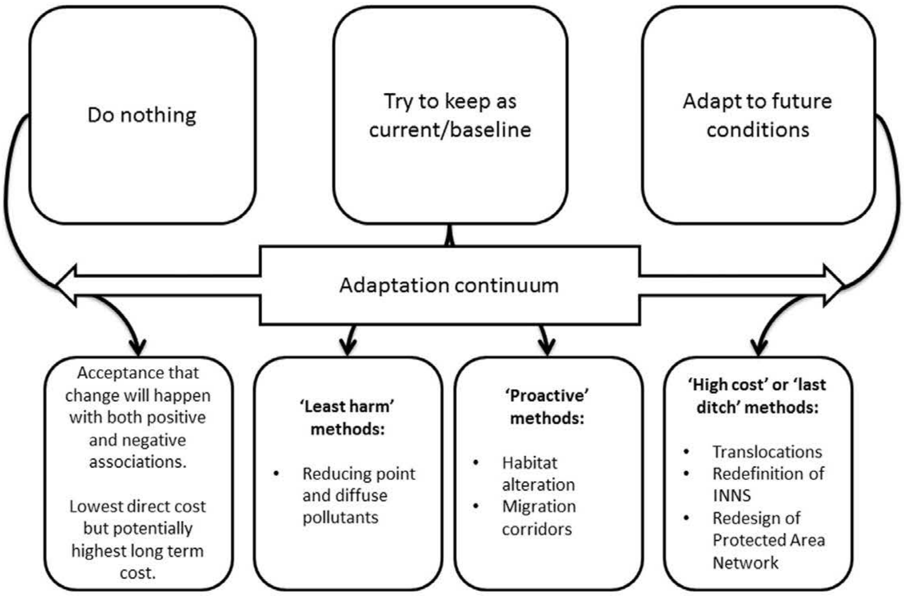

Figure 5 An adaptation continuum for managing the conservation interest of standing freshwaters

Table 3 Adaptation principles for conservation (after Hopkins *et al.*, 2007)

1	Conserve habitat and species baseline
1a	Conserve Protected Areas and other high-quality habitats
1b	Conserve range and ecological variability of habitats and species
2	Reduce sources of harm not linked to climate change
3	Develop ecologically resilient and varied landscapes
3a	Conserve and enhance local variation within sites and habitats
3b	Make space for the natural development of rivers and coasts
4	Establish ecological networks
5	Make sound decisions based on analysis
5a	Thoroughly analyse causes of change
5b	Respond to changing conservation priorities
6	Integrate adaptation and mitigation measures into conservation management, planning and practice

Source: after Hopkins *et al.* 2007

principle because each lake is essentially an isolated body. However, there are both upstream and downstream connections, particularly for mobile species and, in keeping with Table 3 – principle 3, we should be attempting to minimise catchment pressures to promote minimally altered runoff and nutrient fluxes to maintain the natural ecological continuum. We can also think of lakes as fragments within the landscape and, particularly for sensitive sedentary species, should consider human interactions to facilitate the movement of species between these fragments. Assisted migrations have been trialled for some alpine species (Rahel *et al.* 2008; Hagerman *et al.* 2010) and translocations of priority fish species have already occurred in the UK (Lyle and Maitland 2011).

All actions need to be executed making use of the best possible scientific analyses (Table 3 – principle 5) and we suggest that this should be framed using the ESVRA approach. Spatial risk analysis, combined with species and habitat envelope modelling will be particularly important in attempting to future-proof current management decisions. Principles 5b and 6 are clearly linked and are currently underdeveloped for standing freshwater ecosystems. Here we hope to invigorate discussion of practical actions relating to changing priorities based around sound adaptation policy.

Actions: adaptation across multiple spatial and temporal scales

Increasingly policymakers and site managers will be confronted with choices between building resistance or greater resilience to climate change. Adaptation

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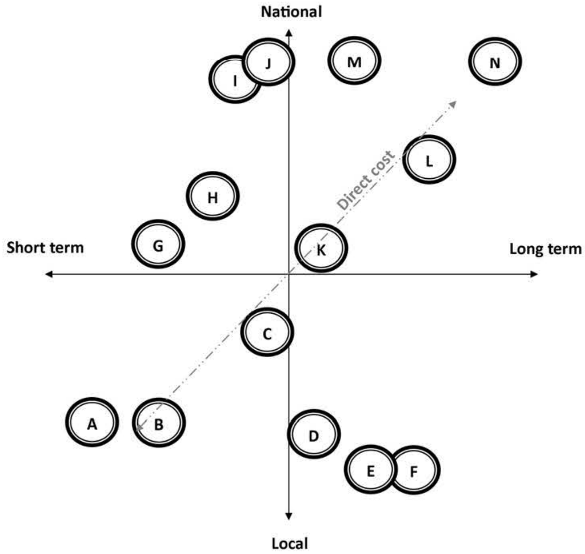

A) Reduce point pollutants
B) Riparian zone planting
C) Ecosystem based catchment restoration e.g. re-connecting wetlands
D) Shoreline 'naturalisation'
E) In lake mechanisms e.g. Aeration pumps
F) Creation of deep / cold water 'refuges'
G) Reduce diffuse pollutants
H) Creation of migration corridors
I) Redefine / Accept INNS
J) Move from 'Poor' to 'Good' systems
K) Assisted migrations
L) Creation of new reserves (ie reservoirs)
M) Species Translocations
N) Redesign Protected Area Network

Figure 6 Fourteen specific adaptation actions for standing freshwaters across multiple spatial and temporal scales

management requires a proactive approach tackling management at multiple spatial and temporal scales. While there will be win-win solutions in the short term that tackle current issues and increase system resilience to future change, we also need to open discussion around harder, longer term management options. Figure 6 shows where we believe 14 specific adaptation actions can be made, highlighting the need for actions on both spatial and temporal scales.

Where more short-term 'actionable' adaptation policies are to be pursued (Heller and Zavaleta 2009), such as riparian planting to increase shade and reduce water temperatures, or the creation of thermal refugia, channel modifications or cool water discharges (see Hallegatte 2009; Wilby *et al.* 2010), these need to be done on an individual site-by-site basis. If, however, the goal is greater ecosystem function and resilience for lakes at the landscape scale, then this needs to embrace greater catchment connectivity. Furthermore, attitudes to management targets will need to change away from simply focusing attention on the composition of the current biotic assemblage at individual sites. Within the EU, this is an especially important issue, because the WFD does not explicitly accommodate changing baseline conditions. One controversial adaptation option is to sacrifice those lakes classified as having 'poor ecological status' and concentrate on maintaining 'favourable condition' in designated sites in addition to maintaining those at 'high' and those 'good' status systems that would readily respond to programmes of measures leading to improvement. This needs to be accompanied by a re-evaluation of current paradigms surrounding environmental protection in static reserves and understandings of 'naturalness', which have been key to the compositionalist philosophy underpinning conservation efforts over the last half century (Callicott *et al.* 2000).

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Conclusions

Using Scotland's lake resource as an example, we can see that the natural variety of lake systems, along with their location, landscape setting and specific catchment characteristics leads to marked differences in sensitivity and resilience to environmental change. Climate change is expected to impact on standing freshwaters through multiple pathways and, depending on the landscape setting, individual lakes are likely to respond in different ways. There must be a greater understanding and incorporation of these concepts when developing adaptation strategies for standing freshwater conservation. The physico-chemical, hydromorphological and ecological processes in each individual lake are likely to respond differently based on this landscape filter. Management decisions must be made with an awareness of how changes in climate (and other pressures) will be filtered through the lake landscape at a variety of scales. This should be an adaptive process, closely monitored and regularly reviewed.

Issues of scale and sensitivity lie at the heart of making robust adaptation strategies for conservation. Resources should be prioritised to the most vulnerable situations, driven by conservation interest and environmental sensitivity to change (climate in particular). To achieve this we must strive for a far greater understanding of sensitivity or resilience of lakes across, in our case, Scotland. Whether we consider an individual lake to be a primary habitat, or part of a wider landscape assemblage, will have consequences for ways in which we are able to manage that change. Allowing flux within a dynamic system might be possible at a larger ecosystem scale, but is most likely untenable if we attempt to manage at the site scale.

Given the implications of global climate change for the natural environment, there is pressure on environmental managers to fully understand the complexity and dynamic nature of the resource base in order to be able to protect native habitats and species. Climate changes as described are highly likely to impact on the ecology and hydrology of standing freshwaters over the coming century and beyond. For Scotland, as elsewhere, we must embrace adaptation management for conservation if species and habitats of conservation priority are to remain a functional part of our natural heritage.

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References

Adams C E, Bean C W, Fraser D and Maitland P S 2007 Conservation and management of the Arctic charr: a forward view *Ecology of Freshwater Fish* 16 2–5

Adrian R, O'Reilly C and Zagarese H 2009 Lakes as sentinels of climate change *Limnology and Oceanography* 54 2283–97

Arvola L, George G, Livingstone D M *et al.* 2010 The impact of climate change on the thermal characteristics of lakes in **George G** ed *The impact of climate change on European lakes* Springer, Dordrecht 85–101

Bates B C, Kundzewicz Z W, Wu S and Palutikof J P eds 2008 *Climate change and water. Technical paper of the Intergovernmental Panel on Climate Change* IPCC Secretariat, Geneva

Bennion H, Fluin J, Appleby P and Ferrier B 2001 *Palaeolimnological investigation of Scottish freshwater lochs* ENSIS Ltd, University College London

Boere G, Galbraith C A and Stroud D eds 2006 *Waterbirds around the world* The Stationery Office, Edinburgh

Callicott J B, Crowder L B and Mumford K 2000 Current normative concepts in conservation biology *Conservation Biology* 13 22–35

Carvalho L, Miller C A, Scott E M, Codd G A, Davies P S and Tyler A N 2011 Cyanobacterial blooms: statistical models describing risk factors for national-scale lake assessment and lake management *Science of the Total Environment* 409 5353–8

Clarke S J 2009 Adapting to climate change?: implications for freshwater biodiversity and management in the UK *Freshwater Reviews* 2 51–64

Dawson T P, Berry P M and Kampa E 2003 Climate change impacts on freshwater wetland habitats *Journal for Nature Conservation* 30 25–30

Dijkstra J A, Westerman E L and Harris L G 2011 The effects of climate change on species composition, succession and phenology: a case study *Global Change Biology* 17 2360–9

Durance I and Ormerod S J 2007 Climate change effects on upland stream macroinvertebrates over a 25-year period *Global Change Biology* 13 942–57

Elliott A 2010 The seasonal sensitivity of cyanobacteria and other phytoplankton to changes in flushing rate and water temperature *Global Change Biology* 16 864–76

European Commission 2000 Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy *Official Journal of the European Communities* L 327 1–72

Galbraith L M and Burns C W 2007 Linking land-use, water body type and water quality in southern New Zealand *Landscape Ecology* 22 231–41

Glick P, Stein B A and Edelson N A 2011 *Scanning the conservation horizon: a guide to climate change vulnerability assessment* National Wildlife Federation, Washington DC

Graham C T and Harrod C 2009 Implications of climate change for the fishes of the British Isles *Journal of Fish Biology* 74 1143–205

Hagerman S, Dowlatabadi H, Chan K M A and Satterfield T 2010 Integrative propositions for adapting conservation policy to the impacts of climate change *Global Environmental Change* 20 351–62

Hallegatte S 2009 Strategies to adapt to an uncertain climate change *Global Environmental Change* 19 240–7

Heller N and Zavaleta E 2009 Biodiversity management in the face of climate change: a review of 22 years of recommendations *Biological Conservation* 14 214–32

Hellmann J J, Byers J E, Bierwagen B G and Dukes J S 2008 Five potential consequences of climate change for invasive species *Conservation Biology* 22 534–43

Hoffmann C C, Kjaergaard C, Uusi-KamppaHansen H C B and Kronvang B 2009 Phosphorus retention in riparian buffers: review of their efficiency *Journal of Environmental Quality* 38 1942–55

Hopkins J J, Allison H M, Walmsley C A, Gaywood M and Thurgate G 2007 *Conserving biodiversity in a changing climate: guidance on building capacity to adapt* Published by Defra on behalf of the UK Biodiversity Partnership

Hughes M, Hornby D D, Bennion H, Kernan M, Hilton J, Phillips G and Thomas R 2004 The development of a GIS-based inventory of standing waters in Great Britain together with a risk-based prioritisation protocol *Water, Air, and Soil Pollution* 4 73–84

Kernan M, Batterbee R W and Moss B eds 2010 *Climate change impacts on freshwater ecosystems* Wiley-Blackwell, London

Kundzewicz Z W, Mata L J, Arnell N W, Döll P, Kabat P, Jiménez B, Miller K A, Oki T, Sen Z and Shiklomanov I A 2007 Freshwater resources and their management in **Parry M L, Canziani O F, Palutikof J P, van der Linden P J and Hanson C E** eds *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* Cambridge University Press, Cambridge 173–210

Lyle A A and Maitland P S 2011 *Translocation of vendace from Derwent Water to refuge locations in southwest Scotland (2007/8)* Scottish Natural Heritage Commissioned Report No. 283

Lyle A A and Smith I R 1994 Standing waters in **Maitland P S, Boon P J and McLusky D S** eds *The freshwaters of Scotland: A national resource of international significance* Wiley, London 35–50

Maltby E, Ormerod S, Acreman M *et al.* 2011 *Freshwaters: open-waters, wetlands and floodplains in the UK National Ecosystem Assessment Technical Report* UK National Ecosystem Assessment UNEP-WCMC, Cambridge

McCabe G J and Wolock D M 2002 Trends and temperature sensitivity of moisture conditions in the conterminous United States *Climate Research* 20 19–29

Mooij W M, Hülsmann S, De Senerpont Domis L N *et al.* 2005 The impact of climate change on lakes in the Netherlands: a review *Aquatic Ecology* 39 381–400

Rahel F J and Olden J D 2008 Assessing the effects of climate change on aquatic invasive species *Conservation Biology* 22 521–33

Rahel F J, Bierwagen B G and Taniguchi Y 2008 Managing aquatic species of conservation concern in the face of climate change and invasive species *Conservation Biology* 22 551–61

Rowan J S, Greig S J, Armstrong, C T, Smith, D C and Tierney D 2012 Development of a classification and decision-support tool for assessing lake hydromorphology *Environmental Modelling and Software* 36 86–98

SNH 2003 *Towards a strategy for Scotland's biodiversity: biodiversity matters!* (http://www.scotland.gov.uk/Publications/2003/02/16437/18486) Accessed 8 December 2010

Soranno P A, Webster K E, Cheruvelil K S and Bremigan M T 2009 The lake landscape-context framework: linking aquatic connections, terrestrial features and human effects at multiple spatial scales *Verhandlungen des Internationalen Verein Limnologie* 30 695–700

Spears B, Paterson D, Perkins R and Carvalho L 2012 Long-term variation and regulation of internal loading in Loch Leven *Hydrobiologia* 681 23–33

Street R B, Steynor A, Bowyer P and Humphrey K 2009 Delivering and using the UK climate projections 2009 *Weather* 64 227–31

Thomas C D, Franco A M A and Hill J K 2006 Range retractions and extinction in the face of climate warming *Trends in Ecology and Evolution* 21 415–16

UKCP09 2011 (http://ukclimateprojections-ui.defra.gov.uk/) Accessed 23 April 2011

Walther G R, Roques A, Hulme P E *et al.* 2009 Alien species in a warmer world: risks and opportunities *Trends in Ecology and Evolution* 24 686–93

Wantzen K M, Rothhaupt K O, Mörtl M, Cantonati M, Tóth L G and Fischer P 2008 Ecological effects of water-level fluctuations in lakes: an urgent issue *Hydrobiologia* 613 1–4

Webster K E, Kratz T K, Bowser C J, Magnuson J J, Rose W J 1996 The influence of landscape position on lake chemical responses to drought in northern Wisconsin *Limnology and Oceanography* 41 977–84

Wilby R L, Orr H G, Watts G *et al.* 2010 Evidence needed to manage freshwater ecosystems in a changing climate: turning adaptation principles into practice *The Science of the Total Environment* 408 4150–64

Winder M and Schindler D E 2004 Climate change uncouples trophic interactions in an aquatic ecosystem *Ecology* 85 2100–6

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Appendix B – Survey Ethics Clearance

Study Protocol

1. Project title

ADAPATION ACTIONS FOR THE CONSERVATION OF SCOTLAND'S LAKES

2. Background information

This online survey is intended as the final data collection stage of a PhD research study which aims to develop adaptation strategies to minimise the impacts of climate change on the conservation interests of Scotland's standing freshwaters.

This research is being carried out by Martin Muir who is a final year PhD student in the School of the Environment at the University of Dundee supervised by Prof. John Rowan and Prof. Chris Spray. The research is funded as a joint studentship by Scottish Natural Heritage and the Scottish Environment Protection Agency.

3. Aims & objectives of the study

This research study aims to:

- Study perceptions of climate change adaptation of those people engaged with conservation and environmental management through research, policy or practical work.
- Explore how the physical characteristics of standing freshwater systems relate to concepts of resilience and adaptive capacity.
- Rate the feasibility and desirability of a range of over 50 identified 'adaptation actions' potentially suitable for conservation management in Scotland and to discuss the spatial and temporal scales over which those actions may be focussed.

4. Brief description of participants and recruitment

A range of scientists, policy makers and practioners active within organisations managing or investigating environmental issues will be approached individually by email (where email address is publically available) and asked to take part in the study. As the study will be completed entirely online the link to the study will be available for those participants to share and made available through the researchers networks.

5. Brief description of the research methods and measurements.

The study will take place online through a website based survey. This can be done from any location with internet access and should work across browsers and devices. The study will require participants to complete one online survey which should take no more than 20 minutes.

The survey is created online using the FormAssembly software which is licensed by the University of Dundee. Form data is securely stored behind a firewall on the University's sky server. When the data is exported from FormAssembly (as .csv data) it will be securely stored in a password protected folder by the lead researcher. Data will be stored securely by the University of Dundee for a maximum of 12 months and by the research team for up to 4 years. Data will only be accessible to the research team and will not be shared with others.

6. Arrangements for participant information, consent and debriefing

Participant information and consent forms are attached to this application. They follow University of Dundee guidelines. Participants will have to acknowledge their consent and willingness to be included in any follow ups. Participants will have the option to opt in to receive updates on the research outputs which make use of the data gathered.

7. Estimated start date and duration

We would like to make the survey before the end of July. It will remain open for one month.

Participant Information

INVITATION TO TAKE PART IN A RESEARCH STUDY

You are being asked to take part in the final stages of a PhD research study which aims to develop adaptation strategies to minimise the impacts of climate change on the conservation interests of Scotland's standing freshwaters.

This research is being carried out by Martin Muir who is a final year PhD student in the School of the Environment at the University of Dundee supervised by Prof. John Rowan and Prof. Chris Spray (who comprise the 'research team'). The research is funded as a joint studentship by Scottish Natural Heritage and the Scottish Environment Protection Agency.

PURPOSE OF THE RESEARCH STUDY

This research study aims to:

- Study perceptions of climate change adaptation of those people engaged with conservation and environmental management through research, policy or practical work.
- Rate the feasibility and desirability of 12 climate change adaptation strategies which cover a range of over 200 identified 'adaptation actions' potentially suitable for conservation management in Scotland and to discuss the spatial and temporal scales over which those actions may be focussed.
- To discuss what are the priorities, knowledge gaps and barriers to implementation for conservation policy in a changing climate.

Participation in this research would benefit those interested in the future environmental management of Scotland's natural resources, particularly freshwater lakes (lakes), given the scale and rate of projected climate changes and the impacts these changes are likely to have to our natural ecology.

TIME COMMITMENT

The study will require you to complete one online survey which should take no more than 20 minutes. If you give consent you may be invited to take part in a further survey or to comment on the results.

TECHNICAL ADVISE

The study will take place online through a website based survey. This can be done from any location with internet access and should work across browsers and devices.

Due to the format of the online survey software screen readers may not function correctly. Please contact m.c.a.muir@dundee.ac.uk if you would prefer a paper copy of the survey to complete or if you have any other technical issues.

COST, REIMBURSEMENT AND COMPENSATION

Your participation in this study is voluntary and undertaken online so no costs should be incurred.

RISKS

There are no known risks for you in this study.

TERMINATION OF PARTICIPATION

You may decide to stop being a part of the research study at any time without explanation and without penalty. Simply do not complete the survey or contact m.c.a.muir@dundee.ac.uk for further information.

CONFIDENTIALITY/ANONYMITY

The data collected in Section 1 of the survey contains limited personal information about you (email). This information is collected to allow us to manage the survey and to communicate with you in future if necessary. It will not be used to identify you or your individual responses.

If you consent, survey comments may be anonymously quoted in publications. They will not be identifiable to you or your organisation.

All questions are completed voluntarily. You may omit any questions you do not wish to answer.

The data will be seen only by the research team and will not be made available to anyone else.

The survey data will be securely stored electronically. Data will be stored securely by the University of Dundee for a maximum of 12 months and by the research team for up to 4 years. Data will only be accessible to the research team and will not be shared with others.

Results may be published in the final PhD thesis, in peer-reviewed literature and in an SNH commissioned report. No individual or organisation will be identifiable in any publication.

CONSENT

You will be asked to tick a box on the online survey to indicate you have read this Participant Information document and that you consent to your responses being collected and used as outlined above.

You will also be asked to tick a box on the online survey if you consent to anonymised comments being used.

You will also be asked to tick a box on the online survey if you consent to be contacted in the future to take part in a further survey or to comment on the results.

FOR FURTHER INFORMATION ABOUT THIS RESEARCH STUDY

Martin Muir will be glad to answer your questions about this study at any time. You may contact him via email at m.c.a.muir@dundee.ac.uk or via twitter @mcamuir

Additional background to the PhD project is available at www.martinmuir.com/research

The first published paper from the project is available online by following the link below. If you would like to receive a .pdf version of the paper please email m.c.a.muir@dundee.ac.uk

Muir, M.C.A., Spray, C.J. and Rowan, J.S. (2012) Climate change and Scotland's standing freshwaters: Informing adaptation strategies for conservation at the landscape scale. Area 44(4) 11-22 doi: 10.1111/j.1475-4762.2012.01130.x

If you want to find out about the final results of this study, you should tick the relevant box at the start of the survey or contact m.c.a.muir@dundee.ac.uk for further information.

The University Research Ethics Committee of the University of Dundee has reviewed and approved this research study.

Outline Survey Structure

Consent (1/8)

Q. I agree to take part in this study and have read the Participant Information Sheet
Q. Extracts from my response may be published anonymously
Q. I may be contacted in the future to take part in a follow up survey or to comment on the results
Q. I would like to opt in to receive updates on the research outputs which make use of the data gathered

Section 1 - About you... (2/8)

Q. Email
Q. Organisation / Institution / Affiliation
Q. Current work / research based in:
Q. Current role(s)
Q. Area(s) of interest / expertise

Section 2 - Perceptions of Climate Change Adaptation and Environmental Management (3/8)
(5 - Strongly Agree | 4 - Agree |3 - Neutral | 2 – Disagree | 1 – Strongly Disagree)

Q. Climate change adaptation must be a key part of any future conservation management plans
Q. Conservation can only be successful with intensive management at local/site level
Q. Conservation of current species assemblage is priority
Q. Conservation management requires strong legislation at the national / international level
Q. There is a willingness at all levels to employ proactive conservation management techniques
Q. We should make decisions today based on the best possible climate model projections we have access to
Q. Understanding the range of climate model projections is not important; the important thing is to manage understanding there will be change
Q. Ecosystem based management should be a priority
Q. Freshwater lakes are an important part of Scotland's natural environment and worthy of increased management resource
Q. The current species assemblage in Scotland's lochs should be protected at all costs
Q. Highly vulnerable systems/species should not be protected – limited resources should focus on those areas with a reasonable chance of longer term resilience.
Q. To what extent are you familiar with the following terms:
- Adaptation
- Mitigation
- Resilience
- Exposure

- Sensitivity
- Adaptive Capacity
- Adaptive Management
- Vulnerability
- Ecosystem Based Management

Q. Ecosystems are dynamic and management should allow for change
Q. Ecosystem service provision should be explicitly incorporated into protected area/conservation management goals
Q. Highly stressed or poor quality systems/species should no longer be protected – limited resources should focus on areas with a reasonable chance of longer term resilience.
Q. The current function(s) of Scotland's freshwater lakes should be protected at all costs
Q. We have sufficient data about Scottish freshwater species to manage our changing environment
Q. We have sufficient data about Scottish loch function to manage our changing environment
Q. Highly vulnerable, disjunct/relict, and outlier systems/species should receive higher protection priority in conservation planning.
Q. Incorporating climate change adaptation into management plans is an opportunity to improve the way we work with the environment
Q. Ecosystem services are the key framework for understanding the value of Scotland's natural environment
Q. We should not adapt conservation management, protected areas policy, system planning and legislation.
Q. Conservation management is, by it's very nature, reactive to change

Section 3 - Adaptation Actions (4/8)

For each 12 strategy groups participants were asked to score:
Q. Desirability
1 – Very Desirable | 2 – Desirable | 3 – Not desirable | 4 – Very Undesirable
Q. Feasibility
Affordability | Ease of implementation |Institutional capacity |Capacity to sustain
1 – Very Desirable | 2 – Desirable | 3 – Not desirable | 4 – Very Undesirable
Q. Spatial scale (at which action could occur)
1 - In the lake | 2 - In the catchment | 3 - Regional / National | 4 - International
Q. Timescale (over which action could occur)
1 - We should be/are doing this already 0-2 years | 2 - A priority over next 2-5 years | 3 – Medium term goal 5-10 years | 4 – Long term goal 10+ years

Q. Please explain your choices or add any comments specific to this adaptation action here...

Section 4 - Comment is free... (8/8)

Q. With particular reference to climate change adaptation, what are the key gaps in knowledge facing environmental managers?

Q. What are current barriers to implementation of adaptation actions for conservation?

Q. What should be the conservation priority for Scotland's standing freshwaters over the next 10 years?

Q. Please leave any other comments here:

References

Aalders I, Hough RL, Towers W (2011) Risk of erosion in peat soils - an investigation using Bayesian belief networks. *Soil Use and Management*, **27**, 538–549.

Abrahams C (2008) Climate change and lakeshore conservation: a model and review of management techniques. *Hydrobiologia*, **613**, 33–43.

Adams CE, Bean CW, Fraser D, Maitland PS (2007) Conservation and management of the Arctic charr: a forward view. *Ecology of Freshwater Fish*, **16**, 2–5.

ADAS (2010) *Climate Vulnerability Assessment of Designated Sites in Wales*. Countryside Council for Wales.

Adger WN (2003) Social capital, collective action, and adaptation to climate change. *Economic geography*, **79**, 387–404.

Adger WN (2006) Vulnerability. *Global Environmental Change*, **16**, 268–281.

Adger WN, Arnell NW, Tompkins EL (2005) Successful adaptation to climate change across scales. *Global Environmental Change*, **15**, 77–86.

Adrian R, Reilly CMO, Zagarese H *et al.* (2009) Lakes as sentinels of climate change. *Limnology and oceanography*, **54**, 2283.

Agard J, Schipper L, Birkmann J *et al.* (2014) *IPCC WGII AR5 Glossary*. IPCC Secretariat, Geneva.

Alagador D, Cerdeira JO, Araújo MB (2014) Shifting protected areas: scheduling spatial priorities under climate change (S Saura, Ed,). *Journal of Applied Ecology*, **51**, 703–713.

Albouy C, Velez L, Coll M *et al.* (2014) From projected species distribution to food-web structure under climate change. *Global change biology*, **20**, 730–41.

Anderegg WRL, Prall JW, Harold J, Schneider SH (2010) Expert credibility in climate change. *Proceedings of the National Academy of Sciences of the United States of America*, **107**, 12107–9.

Araújo MB, Thuiller W, Pearson RG (2006) Climate warming and the decline of amphibians and reptiles in Europe. *Journal of Biogeography*, **33**, 1712–1728.

Arnell NW (1999) Climate change and global water resources. *Global Environmental Change*, **9**, S31–S49.

Arponen A, Lehtomäki J, Leppänen J, Tomppo E, Moilanen A (2012) Effects of Connectivity and Spatial Resolution of Analyses on Conservation Prioritization across Large Extents. *Conservation biology : the journal of the Society for Conservation Biology*, **26**, 294–304.

Arvola L, George G, Livingstone DM *et al.* (2010) The Impact of Climate Change on the Thermal Characteristics of Lakes. In: *The Impact of Climate Change on European Lakes* (ed George G), pp. 85–101. Springer Netherlands, Dordrecht.

Ausden M (2014) Climate change adaptation: putting principles into practice. *Environmental management*, **54**, 685–98.

Bainbridge JM, Potts T, O'Higgins TG (2011) Rapid Policy Network Mapping: A New Method for Understanding Governance Structures for Implementation of Marine Environmental Policy (H Browman, Ed,). *PLoS ONE*, **6**, e26149.

Barbet-Massin M, Thuiller W, Jiguet F (2012) The fate of European breeding birds under climate, land-use and dispersal scenarios. *Global Change Biology*, **18**, 881–890.

Barker A, Stockdale A (2008) Out of the wilderness? Achieving sustainable development within Scottish national parks. *Journal of Environmental Management*, **88**, 181–193.

Barmuta LA, Linke S, Turak E (2011) Bridging the gap between "planning" and "doing" for biodiversity conservation in freshwaters. *Freshwater Biology*, **56**, 180–195.

del Barrio G, Harrison PA, Berry PM *et al.* (2006) Integrating multiple modelling approaches to predict the potential impacts of climate change on species' distributions in contrasting regions: comparison and implications for policy. *Environmental Science & Policy*, **9**, 129–147.

Barton PS, Cunningham S a., Manning AD *et al.* (2013) The spatial scaling of beta diversity (A Baselga, Ed,). *Global Ecology and Biogeography*, **22**, 639–647.

Bassett TJ, Fogelman C (2013) Déjà vu or something new? The adaptation concept in the climate change literature. *Geoforum*, **48**, 42–53.

Bastian O, Grunewald K, Syrbe R-U, Walz U, Wende W (2014) Landscape services: the concept and its practical relevance. *Landscape Ecology*, **29**, 1463–1479.

Bates B, Kundzewicz ZW, Wu S, Palutikof JP (2008) *Climate Change and Water: IPCC Technical Paper VI*. IPCC Secretariat, Geneva.

Baudron AR, Needle CL, Rijnsdorp AD, Tara Marshall C, Marshall CT (2014) Warming temperatures and smaller body sizes: synchronous changes in growth of North Sea fishes. *Global change biology*, **20**, 1023–31.

Bell VA, Jones RG, Kay AL, Reynard NS (2007) National assessment of change in river flows. *UKCP*, 1–5.

Bellard C, Bertelsmeier C, Leadley P, Thuiller W, Courchamp F (2012) Impacts of climate change on the future of biodiversity. *Ecology Letters*, **15**, 365–377.

Bennie J, Hodgson J a, Lawson CR *et al.* (2013) Range expansion through fragmented landscapes under a variable climate. *Ecology letters*, **16**, 921–9.

Bennion H, Fluin J, Simpson GL (2004) Assessing eutrophication and reference conditions for Scottish freshwater lochs using subfossil diatoms. *Journal of Applied Ecology*, **41**, 124–138.

Berger J, Cain SL, Cheng E *et al.* (2014) Optimism and challenge for science-based conservation of migratory species in and out of U.S. National Parks.

Conservation biology : the journal of the Society for Conservation Biology, **28**, 4–12.

Berry PM, Brown S, Chen M *et al.* (2015) Cross-sectoral interactions of adaptation and mitigation measures. *Climatic Change*, **128**, 381–393.

Berry PM, Ogawa-Onishi Y, McVey A (2013) The vulnerability of threatened species: adaptive capability and adaptation opportunity. *Biology*, **2**, 872–93.

Beven KJ, Alcock RE (2012) Modelling everything everywhere: a new approach to decision-making for water management under uncertainty. *Freshwater Biology*, **57**, 124–132.

Biagini B, Bierbaum R, Stults M, Dobardzic S, McNeeley SM (2014) A typology of adaptation actions: A global look at climate adaptation actions financed through the Global Environment Facility. *Global Environmental Change*, **25**, 97–108.

Bibby P (2009) Land use change in Britain. *Land Use Policy*, **26**, 2–13.

Bierwagen BG, Thomas R, Kane A (2008) Capacity of management plans for aquatic invasive species to integrate climate change. *Conservation Biology*, **22**, 568–74.

Booth TH, Nix H a., Busby JR, Hutchinson MF (2014) BIOCLIM : the first species distribution modelling package, its early applications and relevance to most current MAXENT studies (J Franklin, Ed,). *Diversity and Distributions*, **20**, 1–9.

Bresciani M, Stroppiana D, Odermatt D, Morabito G, Giardino C (2011) Assessing remotely sensed chlorophyll-a for the implementation of the Water Framework Directive in European perialpine lakes. *The Science of the total environment*, **409**, 3083–91.

Brooker, R.; Ahrends, A.; Bailey, D.; Brewer, M.; Brown, I.; Castellazzi, M.; Gimona, A.; Ellis, C.; Harding, A.; Harrison, P.; Hopkins, C.; Moss, A.; Muir, M.; Poggio L (2013) *Climate change risk-based assessment for notifiable features in Scotland: interim report*.

Brooks N, Adger WN, Mick Kelly P (2005) The determinants of vulnerability and adaptive capacity at the national level and the implications for adaptation. *Global Environmental Change*, **15**, 151–163.

Brooks JS, Franzen M a, Holmes CM, Grote MN, Mulder MB (2006) Testing hypotheses for the success of different conservation strategies. *Conservation Biology*, **20**, 1528–38.

Brown I, Berry PM, Everard M *et al.* (2015) Identifying robust response options to manage environmental change using an Ecosystem Approach: A stress-testing case study for the UK. *Environmental Science and Policy*, **52**, 74–88.

Brucet S, Poikane S, Lyche-Solheim A, Birk S (2013) Biological assessment of European lakes: ecological rationale and human impacts. *Freshwater Biology*, **58**, 1106–1115.

Buisson L, Grenouillet G, Villéger S, Canal J, Laffaille P (2013) Toward a loss of functional diversity in stream fish assemblages under climate change. *Global*

Change Biology, **19**, 387–400.

Burch S, Berry P, Sanders M (2014) Embedding climate change adaptation in biodiversity conservation: A case study of England. *Environmental Science & Policy*, **37**, 79–90.

Burke EJ, Perry RHJ, Brown SJ (2010) An extreme value analysis of UK drought and projections of change in the future. *Journal of Hydrology*, **388**, 131–143.

Burrows MT, Schoeman DS, Richardson AJ *et al.* (2014) Geographical limits to species-range shifts are suggested by climate velocity. *Nature*, **507**, 492–495.

Cadotte MW (2011) The new diversity: management gains through insights into the functional diversity of communities. *Journal of Applied Ecology*, **48**, 1067–1069.

Cadotte MW, Carscadden K, Mirotchnick N (2011) Beyond species: functional diversity and the maintenance of ecological processes and services. *Journal of Applied Ecology*, **48**, 1079–1087.

Carpenter S, Walker B, Anderies JM, Abel N (2014) From Metaphor to Measurement: Resilience of What to What? *Ecosystems*, **4**, 765–781.

Carter JG, White I (2012) Environmental planning and management in an age of uncertainty: The case of the Water Framework Directive. *Journal of environmental management*, **113**, 228–36.

Carvalho L, Miller C, Spears BM *et al.* (2012) Water quality of Loch Leven: responses to enrichment, restoration and climate change. *Hydrobiologia*, **681**, 35–47.

Carver S, Comber A, McMorran R, Nutter S (2012) A GIS model for mapping spatial patterns and distribution of wild land in Scotland. *Landscape and Urban Planning*, **104**, 395–409.

CEH (2011) *Countryside survey: Land Cover Map 2007 Dataset Documentation*.

Chaichana R, Leah R, Moss B (2010) Birds as eutrophicating agents: a nutrient budget for a small lake in a protected area. *Hydrobiologia*, **646**, 111–121.

Chapman DS (2013) Greater phenological sensitivity to temperature on higher Scottish mountains: new insights from remote sensing. *Global Change Biology*, **19**.

Charlesworth M, Okereke C (2010) Policy responses to rapid climate change: An epistemological critique of dominant approaches. *Global Environmental Change*, **20**, 121–129.

Cheruvelil KS, Soranno PA (2008) Relationships between lake macrophyte cover and lake and landscape features. *Aquatic Botany*, **88**, 219–227.

Chessman BC (2013) Do protected areas benefit freshwater species? A broad-scale assessment for fish in Australia's Murray-Darling Basin (M Cadotte, Ed,). *Journal of Applied Ecology*, **50**, 969–976.

Christoff P (2010) Touching the void: The Garnaut Review in the chasm between climate science, economics and politics. *Global Environmental Change*, **20**, 214–

217.

Čížková H, Květ J, Comín F a. *et al.* (2011) Actual state of European wetlands and their possible future in the context of global climate change. *Aquatic Sciences*, **75**, 3–26.

Clarke SJ (2009) Adapting to Climate Change : Implications for Freshwater Biodiversity and Management in the UK. *Freshwater Reviews*, **2**, 51–64.

Clarvis MH, Fatichi S, Allan A *et al.* (2013) Governing and managing water resources under changing hydro-climatic contexts: The case of the upper Rhone basin. *Environmental Science & Policy*, 1–12.

Cloke HL, Jeffers C, Wetterhall F *et al.* (2010) Climate impacts on river flow: projections for the Medway catchment, UK, with UKCP09 and CATCHMOD. *Hydrological Processes*, **24**, 3476–3489.

Collins WJ, Bellouin N, Doutriaux-Boucher M *et al.* (2011) Development and evaluation of an Earth-system model – HadGEM2. *Geoscientific Model Development Discussions*, **4**, 997–1062.

Comber A, Carver S, Fritz S *et al.* (2010) Different methods, different wilds: Evaluating alternative mappings of wildness using fuzzy MCE and Dempster-Shafer MCE. *Computers, Environment and Urban Systems*, **34**, 142–152.

Comer PJ, Young B, Schulz K *et al.* (2012) *Climate Change Vulnerability and Adaptation Strategies for Natural Communities Piloting methods in the Mojave and Sonoran deserts*. Arlington, VA.

Cook CN, Carter RWB, Fuller R a, Hockings M (2012) Managers consider multiple lines of evidence important for biodiversity management decisions. *Journal of environmental management*, **113**, 341–6.

Cook I, Crang M (2003) *Doing Ethnographies*.

Cook A, Marion G, Butler A, Gibson G (2007) Bayesian inference for the spatio-temporal invasion of alien species. *Bulletin of mathematical biology*, **69**, 2005–25.

Cook CN, Mascia MB, Schwartz MW, Possingham HP, Fuller R a (2013) Achieving Conservation Science that Bridges the Knowledge-Action Boundary. *Conservation biology : the journal of the Society for Conservation Biology*, **27**, 669–678.

Cook BR, Spray CJ (2012) Ecosystem services and integrated water resource management: Different paths to the same end? *Journal of environmental management*, **109C**, 93–100.

Cross MS, McCarthy PD, Garfin G, Gori D, Enquist C a F (2012a) Accelerating Adaptation of Natural Resource Management to Address Climate Change. *Conservation biology : the journal of the Society for Conservation Biology*, **27**, 4–13.

Cross MS, Zavaleta ES, Bachelet D *et al.* (2012b) The Adaptation for Conservation

Targets (ACT) Framework: A Tool for Incorporating Climate Change into Natural Resource Management. *Environmental Management*, **50**, 341–351.

Crossman ND, Bryan B a., Summers DM (2012) Identifying priority areas for reducing species vulnerability to climate change. *Diversity and Distributions*, **18**, 60–72.

Cumming GS (2011) Spatial resilience: integrating landscape ecology, resilience, and sustainability. *Landscape Ecology*, **26**, 899–909.

Cundill G, Cumming GS, Biggs D, Fabricius C (2012) Soft Systems Thinking and Social Learning for Adaptive Management. *Conservation Biology*, **26**, 13–20.

Dana G V, Kapuscinski a R, Donaldson JS (2012) Integrating diverse scientific and practitioner knowledge in ecological risk analysis: a case study of biodiversity risk assessment in South Africa. *Journal of environmental management*, **98**, 134–46.

Daron JD, Sutherland K, Jack C, Hewitson BC (2015) The role of regional climate projections in managing complex socio-ecological systems. *Regional Environmental Change*, **15**, 1–12.

Davies AL, Colombo S, Hanley N (2014) Improving the application of long-term ecology in conservation and land management (D Thompson, Ed,). *Journal of Applied Ecology*, **51**, 63–70.

Davis JM, Baxter C V., Minshall GW *et al.* (2013) Climate-induced shift in hydrological regime alters basal resource dynamics in a wilderness river ecosystem. *Freshwater Biology*, **58**, 306–319.

Dawson TP, Berry PM, Kampa E (2003) Climate change impacts on freshwater wetland habitats. *Journal for Nature Conservation*, **11**, 25–30.

Dawson TP, Jackson ST, House JI, Prentice IC, Mace GM (2011) Beyond predictions: biodiversity conservation in a changing climate. *Science*, **332**, 53–8.

Dea NO, Watson JEM, Whittaker RJ (2004) Rapid assessment in conservation research : a critique of avifaunal assessment techniques illustrated by Ecuadorian and Madagascan case study data. *Diversity and Distributions*, 55–63.

Dessai S, Hulme M (2007) Assessing the robustness of adaptation decisions to climate change uncertainties: A case study on water resources management in the East of England. *Global Environmental Change*, **17**, 59–72.

Dessel W, Rompaey A, Poelmans L *et al.* (2008) Predicting land cover changes and their impact on the sediment influx in the Lake Balaton catchment. *Landscape Ecology*, **23**, 645–656.

Dijkstra JA, Westerman EL, Harris LG (2011) The effects of climate change on species composition, succession and phenology: a case study. *Global Change Biology*, **17**, 2360–2369.

Dlamini WM (2010) A Bayesian belief network analysis of factors influencing wildfire occurrence in Swaziland. *Environmental Modelling & Software*, **25**, 199–208.

Doak DF, Bakker VJ, Goldstein BE, Hale B (2013) What is the future of conservation?

Trends in Ecology & Evolution, 1–5.

Dokulil MT (2013) Impact of climate warming on European inland waters. *Inland Waters*, 27–40.

Domisch S, Jähnig SC, Haase P (2011) Climate-change winners and losers: stream macroinvertebrates of a submontane region in Central Europe. *Freshwater Biology*, **56**, 2009–2020.

Donlan CJ, Wingfield DK, Crowder LB, Wilcox C (2010) Using expert opinion surveys to rank threats to endangered species: a case study with sea turtles. *Conservation biology : the journal of the Society for Conservation Biology*, **24**, 1586–95.

Doswald N, Munroe R, Roe D *et al.* (2014) Effectiveness of ecosystem-based approaches for adaptation: review of the evidence-base. *Climate and Development*, **6**, 1–17.

Dow K, O'Connor RE, Yarnal B, Carbone GJ, Jocoy CL (2007) Why worry? Community water system managers' perceptions of climate vulnerability. *Global Environmental Change*, **17**, 228–237.

Dudgeon D, Arthington AH, Gessner MO *et al.* (2006) Freshwater biodiversity: importance, threats, status and conservation challenges. *Biological reviews of the Cambridge Philosophical Society*, **81**, 163–82.

Duigan C, Kovach W, Palmer M (2007) Vegetation communities of British lakes: a revised classification scheme for conservation. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **17**, 147–173.

Duncan N, Harrison GP, Wallace AR (2010) Understanding Future Climate Impacts on Scotland' s Hydropower Resource. In: *Hydropower'10 - 6th Internatinoal Hydropower Conference*

Duputié A, Zimmermann NE, Chuine I (2014) Where are the wild things? Why we need better data on species distribution. *Global Ecology and Biogeography*, **23**, 457–467.

Durance I, Ormerod SJ (2007) Climate change effects on upland stream macroinvertebrates over a 25-year period. *Global Change Biology*, **13**, 942–957.

Elez J, Cuezva S, Fernandez-Cortes a *et al.* (2013) A GIS-based methodology to quantitatively define an Adjacent Protected Area in a shallow karst cavity: The case of Altamira cave. *Journal of environmental management*, **118**, 122–34.

Elliot JM (2011) A comparative study of the relationship between light intensity and feeding ability in brown trout (Salmo trutta) and Arctic charr (Salvelinus alpinus). *Freshwater Biology*, **56**, 1962–1972.

Elliott JA, Bell VA (2011) Predicting the potential long-term influence of climate change on vendace (Coregonus albula) habitat in Bassenthwaite Lake, U.K. *Freshwater Biology*, **56**, 395–405.

Elliott JA, May L (2008) The sensitivity of phytoplankton in Loch Leven (U.K.) to changes in nutrient load and water temperature. *Freshwater Biology*, **53**, 32–41.

Ervin J, Congress WP (2003) Protected Area Assessments in Perspective. *BioScience*, **53**, 833.

Etheridge EC, Bean CW, Maitland PS, Adams CE (2010) Morphological and ecological responses to a conservation translocation of powan (Coregonus lavaretus) in Scotland. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **20**, 274–281.

European Environment Agency (2012) *Climate change, impacts and vulnerability in Europe 2012: An indicator-based report*. European Environment Agency.

Evans C, Monteith D, Wright D, Clark J, Road D (2006) Issues affecting upland water quality: Climate change, acidity, nitrogen and water colour. In: *Climate change and aquatic ecosystems in the UK: Science, policy and management* , pp. 21–25.

Fabricius C, Cundill G (2014) Learning in Adaptive Management : Insights from Published Practice. *Ecology and Society*, **19**, 29.

Falloon P, Betts R (2010) Climate impacts on European agriculture and water management in the context of adaptation and mitigation--the importance of an integrated approach. *The Science of the total environment*, **408**, 5667–87.

Ferna C (2009) Habitat selection and sampling design for ecological assessment of heterogeneous ponds using macroinvertebrates. , **796**, 786–796.

Feuchtmayr H, Thackeray SJ, Jones ID *et al.* (2011) Spring phytoplankton phenology - are patterns and drivers of change consistent among lakes in the same climatological region? *Freshwater Biology*, no-no.

Folke C (2006) Resilience: The emergence of a perspective for social–ecological systems analyses. *Global Environmental Change*, **16**, 253–267.

Folke C, Carpenter SR, Walker B *et al.* (2010) Resilience Thinking : Integrating Resilience, Adaptability and Transformability. *Ecology And Society*, **15**, 20.

Folke C, Rockström J (2009) Turbulent times. *Global Environmental Change*, **19**, 1–3.

Franklin J, Davis FW, Ikegami M *et al.* (2013) Modeling plant species distributions under future climates: how fine scale do climate projections need to be? *Global Change Biology*, **19**, 473–483.

Free G, Solimini AG, Rossaro B *et al.* (2009) Modelling lake macroinvertebrate species in the shallow sublittoral: relative roles of habitat, lake morphology, aquatic chemistry and sediment composition. *Hydrobiologia*, **633**, 123–136.

Fuller RA, McDonald-Madden E, Wilson K *et al.* (2010) Replacing underperforming protected areas achieves better conservation outcomes. *Nature*, **466**, 365–367.

Füssel H-M (2007) Vulnerability: A generally applicable conceptual framework for climate change research. *Global Environmental Change*, **17**, 155–167.

Füssel H-M, Klein RJT (2006) Climate Change Vulnerability Assessments: An Evolution of Conceptual Thinking. *Climatic Change*, **75**, 301–329.

Galbraith LM, Burns CW (2007) Linking Land-use, Water Body Type and Water Quality in Southern New Zealand. *Landscape Ecology*, **22**, 231–241.

Gallopín GC (2006) Linkages between vulnerability, resilience, and adaptive capacity. *Global Environmental Change*, **16**, 293–303.

Game ET, Lipsett-Moore G, Saxon E, Peterson N, Sheppard S (2011) Incorporating climate change adaptation into national conservation assessments. *Global Change Biology*, **17**, 3150–3160.

Garris HW, Mitchell RJ, Fraser LH, Barrett LR (2015) Forecasting climate change impacts on the distribution of wetland habitat in the Midwestern United states. *Global Change Biology*, **21**, 766–776.

Gaston KJ, Charman K, Jackson SF *et al.* (2006) The ecological effectiveness of protected areas: The United Kingdom. *Biological Conservation*, **132**, 76–87.

George G, Jennings E, Allott N (2010) The Impact of Climate Change on Lakes in Britain and Ireland. In: *The Impact of Climate Change on European Lakes* (ed George G), pp. 359–386. Springer Netherlands, Dordrecht.

Gillings S, Balmer DE, Fuller RJ (2015) Directionality of recent bird distribution shifts and climate change in Great Britain. *Global Change Biology*, **21**, 2155–2168.

Gilvear DJ, Spray CJ, Casas-Mulet R (2013) River rehabilitation for the delivery of multiple ecosystem services at the river network scale. *Journal of Environmental Management*, **126**, 30–43.

Glass JH, Scott AJ, Price MF (2013) The power of the process: Co-producing a sustainability assessment toolkit for upland estate management in Scotland. *Land Use Policy*, **30**, 254–265.

Glick P, Chmura H, Stein BA (2011a) Moving the Conservation Goalposts: A Review of Climate Change Adaptation Literature. *US National Wildlife Federation*, 1–25.

Glick P, Stein BA, Edelson NA (2011b) Scanning the Conservation Horizon: A Guide to Climate Change Vulnerability Assessment. *US National Wildlife Federation*.

Graham CT, Harrod C (2009) Implications of climate change for the fishes of the British Isles. *Journal of fish biology*, **74**, 1143–205.

Hadley KR, Paterson AM, Hall RI, Smol JP (2012) Effects of multiple stressors on lakes in south-central Ontario: 15 years of change in lakewater chemistry and sedimentary diatom assemblages. *Aquatic Sciences*, **75**, 349–360.

Hagerman S, Dowlatabadi H, Chan KMA, Satterfield T (2010a) Integrative propositions for adapting conservation policy to the impacts of climate change. *Global Environmental Change*, **20**, 351–362.

Hagerman S, Dowlatabadi H, Satterfield T, McDaniels T (2010b) Expert views on biodiversity conservation in an era of climate change. *Global Environmental Change*, **20**, 192–207.

Hall J, Murphy C (2011) Robust adaptation assessment – climate change and water supply. *International Journal of Climate Change Strategies and Management*, **3**, 302–319.

Hallegatte S (2009) Strategies to adapt to an uncertain climate change. *Global Environmental Change*, **19**, 240–247.

Hameed SO, Holzer K a, Doerr AN, Baty JH, Schwartz MW (2013) The value of a multi-faceted climate change vulnerability assessment to managing protected lands: Lessons from a case study in Point Reyes National Seashore. *Journal of environmental management*, **121C**, 37–47.

Hannah DM, Brown LE, Milner AM *et al.* (2007) Integrating climate–hydrology–ecology for alpine river systems. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **17**, 636–656.

Hannah DM, Wood PJ, Sadler JP (2004) Ecohydrology and hydroecology: A ?new paradigm?? *Hydrological Processes*, **18**, 3439–3445.

Hansson L, Angelstam P (1991) Landscape ecology as a theoretical basis for nature conservation. *Landscape Ecology*, **5**, 191–201.

Harrison PA, Berry PM, Simpson G *et al.* (2014) Linkages between biodiversity attributes and ecosystem services: A systematic review. *Ecosystem Services*, **9**, 191–203.

Harrison PA, Holman IP, Berry PM (2015) Assessing cross-sectoral climate change impacts, vulnerability and adaptation: an introduction to the CLIMSAVE project. *Climatic Change*, **128**, 153–167.

Hawes M, Dixon G, Ling R (2013) A GIS-based methodology for predicting walking track stability. *Journal of environmental management*, **115**, 295–9.

Hayden B, Holopainen T, Amundsen P-A *et al.* (2013) Interactions between invading benthivorous fish and native whitefish in subarctic lakes. *Freshwater Biology*, **58**, 1234–1250.

Heino J, Virkkala R, Toivonen H (2009) Climate change and freshwater biodiversity: detected patterns, future trends and adaptations in northern regions. *Biological reviews of the Cambridge Philosophical Society*, **84**, 39–54.

Heller NE, Hobbs RJ (2014) Development of a natural practice to adapt conservation goals to global change. *Conservation Biology*, **28**, 696–704.

Heller NE, Zavaleta ES (2009) Biodiversity management in the face of climate change: A review of 22 years of recommendations. *Biological Conservation*, **142**, 14–32.

Hellmann JJ, Byers JE, Bierwagen BG, Dukes JS (2008) Five potential consequences of climate change for invasive species. *Conservation Biology*, **22**, 534–43.

Hendrickx F, Maelfait JP, Van Wingerden W *et al.* (2007) How landscape structure, land-use intensity and habitat diversity affect components of total arthropod diversity in agricultural landscapes. *Journal of Applied Ecology*, **44**, 340–351.

Henriksen HJ, Barlebo HC (2008) Reflections on the use of Bayesian belief networks for adaptive management. *Journal of environmental management*, **88**, 1025–36.

Hermoso V, Linke S, Prenda J, Possingham HP (2011) Addressing longitudinal connectivity in the systematic conservation planning of fresh waters. *Freshwater Biology*, **56**, 57–70.

Hermoso V, Ward DP, Kennard MJ (2012) Using water residency time to enhance spatio-temporal connectivity for conservation planning in seasonally dynamic freshwater ecosystems (D Angeler, Ed,). *Journal of Applied Ecology*, **49**, 1028–1035.

Higgins S, Mahon M, McDonagh J (2012) Interdisciplinary interpretations and applications of the concept of scale in landscape research. *Journal of environmental management*, **113C**, 137–145.

Hijmans RJ, Cameron SE, Parra JL, Jones PG, Jarvis A (2005) Very high resolution interpolated climate surfaces for global land areas. *International Journal of Climatology*, **25**, 1965–1978.

Hijmans RJ, Elith J (2011) *Species distribution modeling with R*.

Hill M, Engle NL (2013) Adaptive Capacity: Tensions across Scales. *Environmental Policy and Governance*, **23**, 177–192.

Hinkel J (2011) "Indicators of vulnerability and adaptive capacity": Towards a clarification of the science–policy interface. *Global Environmental Change*, **21**, 198–208.

Hobbs R (2009) Woodland restoration in Scotland: ecology, history, culture, economics, politics and change. *Journal of Environmental Management*, **90**, 2857–65.

Hof C, Levinsky I, Araújo MB, Rahbek C (2011) Rethinking species' ability to cope with rapid climate change. *Global Change Biology*, **17**, 2987–2990.

Hofmann ME, Hinkel J, Wrobel M (2011) Classifying knowledge on climate change impacts, adaptation, and vulnerability in Europe for informing adaptation research and decision-making: A conceptual meta-analysis. *Global Environmental Change*, **21**, 1106–1116.

Hopkins JJ, Allison H, Walmsley CA, Gaywood M, Thurgate G (2007) Conserving biodiversity in a changing climate : guidance on building capacity to adapt. *UK Biodiversity Partnership; DEFRA*, 1–32.

Hubacek K, Hiscock K (2012) The role of expert opinion in environmental modelling. *Environmental Modelling & Software*, **36**, 4–18.

Hughes M, Hornby DD, Bennion H *et al.* (2004) The development of a GIS-based inventory of standing waters in Great Britain together with a risk-based prioritisation protocol. *Water, Air, and Soil Pollution: Focus*, **4**, 73–84.

Hulme PE (2005) Adapting to climate change: is there scope for ecological management in the face of a global threat? *Journal of Applied Ecology*, **42**, 784–794.

Huntley B, Altwegg R, Barnard P, Collingham YC, Hole DG (2012) Modelling relationships between species spatial abundance patterns and climate. *Global Ecology and Biogeography*, **21**, 668–681.

Iacob O, Rowan JS, Brown I, Ellis C (2014) Evaluating wider benefits of natural flood management strategies: an ecosystem-based adaptation perspective. *Hydrology Research*, **45**, 774–787.

Ippolito a, Sala S, Faber JH, Vighi M (2010) Ecological vulnerability analysis: a river basin case study. *The Science of the total environment*, **408**, 3880–90.

Iverson L, Echeverria C, Nahuelhual L, Luque S (2014) Ecosystem services in changing landscapes: An introduction. *Landscape Ecology*, **29**, 181–186.

Jackson LJ (2011) Conservation of shallow lakes given an uncertain, changing climate: challenges and opportunities. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **21**, 219–223.

Jackson RB, Jobb EG, Nosetto MD (2009) Ecohydrology Bearings — Invited Commentary Ecohydrology in a human-dominated landscape. , **389**, 383–389.

Jackson S, Palmer LR (2015) Reconceptualizing ecosystem services: Possibilities for cultivating and valuing the ethics and practices of care. *Progress in Human Geography*, **39**, 122–145.

Jankowski T, Livingstone DM, Bührer H, Forster R, Niederhauser P (2006) Consequences of the 2003 European heat wave for lake temperature profiles, thermal stability, and hypolimnetic oxygen depletion: Implications for a warmer world. *Limnology and Oceanography*, **51**, 815–819.

Jaroszweski D, Chapman L, Petts J (2010) Assessing the potential impact of climate change on transportation: the need for an interdisciplinary approach. *Journal of Transport Geography*, **18**, 331–335.

Jenkins GJ, Perry MC, Prior M. (2009) The climate of the United Kingdom and recent trends. *Met Office Hadley Centre*.

Jeppesen E, Meerhoff M, Holmgren K *et al.* (2010) Impacts of climate warming on lake fish community structure and potential effects on ecosystem function. *Hydrobiologia*, **646**, 73–90.

Jeppesen E, Sondergaard M, Jensen JP *et al.* (2005) Lake responses to reduced nutrient loading - an analysis of contemporary long-term data from 35 case studies. *Freshwater Biology*, **50**, 1747–1771.

Jeppesen E, Søndergaard M, Meerhoff M, Lauridsen TL, Jensen JP (2007) Shallow lake restoration by nutrient loading reduction—some recent findings and challenges ahead. *Hydrobiologia*, **584**, 239–252.

Jiménez Cisneros BE, Oki T, Arnell NW *et al.* (2014) Freshwater resources. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Intergovernmental, Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Panel on Climate Change* (eds Field CB, Barros VR, Dokken DJ, et al.), pp. 229–269. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Johnson AC, Acreman MC, Dunbar MJ *et al.* (2009) The British river of the future: how climate change and human activity might affect two contrasting river ecosystems in England. *The Science of the total environment*, **407**, 4787–98.

Jones CD, Hughes JK, Bellouin N *et al.* (2011) The HadGEM2-ES implementation of CMIP5 centennial simulations. *Geoscientific Model Development*, **4**, 543–570.

Kass GS, Shaw RF, Tew T, Macdonald DW (2011) Securing the future of the natural environment: using scenarios to anticipate challenges to biodiversity, landscapes and public engagement with nature. *Journal of Applied Ecology*, **48**, 1518–1526.

Kates RW, Travis WR, Wilbanks TJ (2012) Transformational adaptation when incremental adaptations to climate change are insufficient. *Proceedings of the National Academy of Sciences*, **109**, 7156–7161.

Kati V, Hovardas T, Dieterich M *et al.* (2014) The challenge of implementing the European network of protected areas natura 2000. *Conservation Biology*, **29**, 260–270.

Kay AL, Davies H (2008) Calculating potential evaporation from climate model data: A source of uncertainty for hydrological climate change impacts. *Journal of Hydrology*, **358**, 221–239.

Keppel G, Wardell-Johnson GW (2012) Refugia: keys to climate change management. *Global Change Biology*, **18**, 2389–2391.

Kernan M, Hughes M, Helliwell RC (2002) Chemical variation and catchment characteristics in high altitude lochs in Scotland, UK. *Water, Air, and Soil Pollution: Focus*, **2**, 61–73.

Khamis K, Hannah DM, Clarvis MH *et al.* (2014) Alpine aquatic ecosystem conservation policy in a changing climate. *Environmental Science & Policy*, **43**, 39–55.

Kingston DG, Todd MC, Taylor RG, Thompson JR, Arnell NW (2009) Uncertainty in the estimation of potential evapotranspiration under climate change. *Geophysical Research Letters*, **36**, L20403.

Kleijn D, Kohler F, Báldi a *et al.* (2009) On the relationship between farmland biodiversity and land-use intensity in Europe. *Proceedings. Biological sciences / The Royal Society*, **276**, 903–909.

Kong J, Xin P, Song Z, Li L (2010) A new model for coupling surface and subsurface water flows: With an application to a lagoon. *Journal of Hydrology*, **390**, 116–120.

Koomen E, Opdam P, Steingröver E (2012) Adapting complex multi-level landscape systems to climate change. *Landscape Ecology*, **277**, 469–471.

Korosi JB, Smol JP (2012) Examining the effects of climate change, acidic deposition, and copper sulphate poisoning on long-term changes in cladoceran assemblages. *Aquatic Sciences*, **74**, 781–792.

Kreyling J, Jentsch A, Beier C (2014) Beyond realism in climate change experiments: gradient approaches identify thresholds and tipping points (F Lloret, Ed,). *Ecology Letters*, **17**, 125–126.

Lacher I, Wilkerson ML (2014) Wildlife connectivity approaches and best practices in U.S. state wildlife action plans. *Conservation biology : the journal of the Society for Conservation Biology*, **28**, 13–21.

Lassalle G, Crouzet P, Gessner J, Rochard E (2010) Global warming impacts and conservation responses for the critically endangered European Atlantic sturgeon. *Biological Conservation*, **143**, 2441–2452.

Lawler JJ, Ruesch a S, Olden JD, McRae BH (2013) Projected climate-driven faunal movement routes. *Ecology letters*, **16**, 1014–1022.

Lemieux CJ, Scott DJ (2011) Changing Climate, Challenging Choices: Identifying and Evaluating Climate Change Adaptation Options for Protected Areas Management in Ontario, Canada. *Environmental Management*, **48**, 675–690.

Likert R (1932) A Technique for the Measurement of Attitudes. *Archives of Psychology*, **140**, 1–55.

Lindenmayer DB, Steffen W, Burbidge A a. *et al.* (2010) Conservation strategies in response to rapid climate change: Australia as a case study. *Biological Conservation*, **143**, 1587–1593.

Lindström G, Pers C, Rosberg J, Strömqvist J, Arheimer B (2010) Development and testing of the HYPE (Hydrological Predictions for the Environment) water quality model for different spatial scales. *Hydrology Research*, **41**, 295.

Loehle C (2011) Criteria for assessing climate change impacts on ecosystems. *Ecology and Evolution*, **1**, 63–72.

Van Looy K, Cavillon C, Tormos T *et al.* (2013) A scale-sensitive connectivity analysis to identify ecological networks and conservation value in river networks. *Landscape Ecology*, **28**, 1239–1249.

Lu J, Sun G, Mcnulty SG, Amatya DM (2005) A comparison of six potential evapotranspiration methods for regional use in the southeastern United States. *Journal Of The American Water Resources Association*, 621–633.

Lyle A, Maitland PS (2011) *Translocation of vendace from Derwentwater to refuge locations in Southwest Scotland (2007/8)*. Battleby, Perth.

Maberly SC, Elliot JA (2012) Insights from long-term studies in the Windermere catchment: external stressors, internal interactions and the structure and function of lake ecosystems. *Freshwater Biology*, **57**, 233–243.

Mace GM, Norris K, Fitter AH (2012) Biodiversity and ecosystem services: a multilayered relationship. *Trends in ecology & evolution*, **27**, 19–26.

Madsen J, Tjørnløv RS, Frederiksen M, Mitchell C, Sigfússon AT (2014) Connectivity between flyway populations of waterbirds: assessment of rates of exchange, their causes and consequences (T Pärt, Ed,). *Journal of Applied Ecology*, **51**, 183–193.

Maileht K, Nõges T, Nõges P *et al.* (2013) Water colour, phosphorus and alkalinity are the major determinants of the dominant phytoplankton species in European lakes. *Hydrobiologia*, **704**, 115–126.

Maltby E, Ormerod S, Acreman MC *et al.* (2011) NEA Freshwaters – Openwaters, Wetlands and Floodplains. In: *National Ecosystem Assessment* , pp. 1–65.

Manfreda S, Smettem K, Iacobellis V, Montaldo N, Sivapalan M (2010) Coupled ecological – hydrological processes. *Ecohydrology*, **3**, 131–132.

Mantyka-Pringle CS, Martin TG, Moffatt DB, Linke S, Rhodes JR (2014) Understanding and predicting the combined effects of climate change and land-use change on freshwater macroinvertebrates and fish. *Journal of Applied Ecology*, **51**, 572–581.

Marsh TJ, Anderson JL (2002) Assessing the water resources of Scotland--perspectives, progress and problems. *The Science of the total environment*, **294**, 13–27.

Martin TG, Burgman MA, Fidler F *et al.* (2012) Eliciting Expert Knowledge in Conservation Science. *Conservation Biology*, **26**, 29–38.

Marvier M (2014) New conservation is true conservation. *Conservation biology : the journal of the Society for Conservation Biology*, **28**, 1–3.

Mastrangelo ME, Weyland F, Villarino SH *et al.* (2013) Concepts and methods for landscape multifunctionality and a unifying framework based on ecosystem services. *Landscape Ecology*, **29**, 345–358.

Matthews WJ, Marsh-Matthews E (2011) An invasive fish species within its native range: community effects and population dynamics of Gambusia affinis in the central United States. *Freshwater Biology*, **56**, 2609–2619.

Mawdsley J (2011) Design of conservation strategies for climate adaptation. *Wiley Interdisciplinary Reviews: Climate Change*, **2**, 498–515.

Mazziotta A, Triviño M, Tikkanen O-P *et al.* (2014) Applying a framework for landscape planning under climate change for the conservation of biodiversity in the Finnish boreal forest. *Global change biology*, 1–15.

Mc Morran R, Price MF, Warren CR (2008) The call of different wilds: the importance of definition and perception in protecting and managing Scottish wild landscapes. *Journal of Environmental Planning and Management*, **51**, 177–199.

McCabe GJ, Wolock DM (2002) Trends and temperature sensitivity of moisture conditions in the conterminous United States. *Climate Research*, **20**, 19–29.

McClure MM, Alexander M, Borggaard D *et al.* (2013) Incorporating climate science in applications of the u.s. Endangered species act for aquatic species. *Conservation biology : the journal of the Society for Conservation Biology*, **27**, 1222–33.

McDowell WG, Benson AJ, Byers JE (2014) Climate controls the distribution of a widespread invasive species: implications for future range expansion. *Freshwater Biology*, **59**, 847–857.

McFarland B, Carse F, Sandin L (2010) Littoral macroinvertebrates as indicators of lake acidification within the UK. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **20**, S105–S116.

McKenzie AJ, Emery SB, Franks JR, Whittingham MJ (2013) Landscape-scale conservation: collaborative agri-environment schemes could benefit both biodiversity and ecosystem services, but will farmers be willing to participate? (J Barlow, Ed,). *Journal of Applied Ecology*, **50**, 1274–1280.

Meinard Y, Quétier F (2014) Experiencing biodiversity as a bridge over the science-society communication gap. *Conservation Biology*, **28**, 705–712.

Milcu AI, Hanspach J, Abson D, Fischer J (2013) Cultural Ecosystem Services: A Literature Review and Prospects for Future Research. *Ecology and Society*, **18**, 44–52.

Miller BW, Caplow SC, Leslie PW (2012) Feedbacks between conservation and social-ecological systems. *Conservation biology : the journal of the Society for Conservation Biology*, **26**, 218–27.

Mirfenderesk H, Corkill D (2009) The need for adaptive strategic planning: Sustainable management of risks associated with climate change. *International Journal of Climate Change Strategies and Management*, **1**, 146–159.

Mitchell DW (2004) More on spreads and non-arithmetic means. *The Mathematical Gazette*, 142–144.

Mittermeier RA, Myers N, Thomsen JB, da Fonseca GAB, Olivieri S (1998) Biodiversity Hotspots and Major Tropical Wilderness Areas: Approaches to Setting Conservation Priorities. *Conservation Biology*, **12**, 516–520.

Monk W a, Wilbur NM, Allen Curry R, Gagnon R, Faux RN (2013) Linking landscape variables to cold water refugia in rivers. *Journal of environmental management*, **118C**, 170–176.

Mooij WM, Hülsmann S, De Senerpont Domis LN *et al.* (2005) The impact of climate change on lakes in the Netherlands: a review. *Aquatic Ecology*, **39**, 381–400.

Mooij WM, Trolle D, Jeppesen E *et al.* (2010) Challenges and opportunities for integrating lake ecosystem modelling approaches. *Aquatic Ecology*, **44**, 633–667.

Moran E V., Alexander JM (2014) Evolutionary responses to global change: Lessons from invasive species. *Ecology Letters*, **17**, 637–649.

Morecroft MD, Crick HQP, Duffield SJ, Macgregor N a. (2012) Resilience to climate change: translating principles into practice. *Journal of Applied Ecology*, 547–551.

Morton D, Rowland C, Wood C *et al.* (2011) *Final Report for LCM2007 - the new UK land cover map. Countryside Survey Technical Report No 11/07*.

Moss B (2008) The kingdom of the shore : achievement of good ecological potential in reservoirs. *Freshwater Reviews*, 29–42.

Moss B (2014) Fresh Waters, Climate Change and UK Nature Conservation. *Freshwater Reviews*, **7**, 25–75.

Moss R, Babiker M, Brinkman S *et al.* (2008) Towards new scenarios for analysis of emissions, climate change, impacts and response strategies. *Intergovernmental Panel on Climate Change*, 132.

Moyes K, Nussey DH, Clements MN *et al.* (2011) Advancing breeding phenology in response to environmental change in a wild red deer population. *Global Change Biology*, **17**, 2455–2469.

Muir AP, Biek R, Thomas R, Mable BK (2014) Local adaptation with high gene flow: Temperature parameters drive adaptation to altitude in the common frog (Rana temporaria). *Molecular Ecology*, **23**, 561–574.

Muir MCA, Spray CJ, Rowan JS (2012) Climate change and standing freshwaters: informing adaptation strategies for conservation at multiple scales. *Area*, **44**, 411–422.

Muir AP, Thomas R, Biek R, Mable BK (2013) Using genetic variation to infer associations with climate in the common frog, Rana temporaria. *Molecular Ecology*, **22**, 3737–3751.

Mumby PJ, Chollett I, Bozec Y-M, Wolff NH (2014) Ecological resilience, robustness and vulnerability: how do these concepts benefit ecosystem management? *Current Opinion in Environmental Sustainability*, **7**, 22–27.

Munang R, Rivington M, Takle ES *et al.* (2010) Climate Information and Capacity Needs for Ecosystem Management under a Changing Climate. *Procedia Environmental Sciences*, **1**, 206–227.

Murdoch PS, Baron JS, Miller TL (2000) POTENTIAL EFFECTS OF CLIMATE CHANGE ON SURFACE-WATER QUALITY IN NORTH AMERICA. *Journal of the American Water Resources Association*, **36**, 347–366.

Murphy J, Sexton D, Jenkins G *et al.* (2010) *Climate change projections*. Met Office Hadley Centre, Exeter, UK.

Naidoo R, Balmford A, Costanza R *et al.* (2008) Global mapping of ecosystem services and conservation priorities. *Proceedings of the National Academy of Sciences*, **105**, 9495–9500.

Nairn K (2005) A counter-narrative of a “failed” interview. *Qualitative Research*, **5**, 221–244.

Neff MW, Larson BMH (2014) Scientists, managers, and assisted colonization: Four contrasting perspectives entangle science and policy. *Biological Conservation*, **172**, 1–7.

Nel JL, Roux DJ, Abell R *et al.* (2009) Progress and challenges in freshwater conservation planning. *Aquatic Conservation: Marine and Freshwater*

Ecosystems, **19**, 474–485.

Newton A, Icely J, Cristina S *et al.* (2014) An overview of ecological status, vulnerability and future perspectives of European large shallow, semi-enclosed coastal systems, lagoons and transitional waters. *Estuarine, Coastal and Shelf Science*, **140**, 95–122.

Nichols JD, Koneff MD, Heglund PJ *et al.* (2011) Climate change, uncertainty, and natural resource management. *The Journal of Wildlife Management*, **75**, 6–18.

Nielsen JØ, Reenberg A (2010) Cultural barriers to climate change adaptation: A case study from Northern Burkina Faso. *Global Environmental Change*, **20**, 142–152.

Nilsen EB, Milner-Gulland EJ, Schofield L *et al.* (2007) Wolf reintroduction to Scotland: public attitudes and consequences for red deer management. *Proceedings of the Royal Society B: Biological Sciences*, **274**, 995–1002.

North RLRP, Livingstone DM, Köster O, Kipfer R (2014) Long-term changes in hypoxia and soluble reactive phosphorus in the hypolimnion of a large temperate lake: consequences of a climate regime shift. *Global change biology*, **20**, 811–23.

Noyes PD, McElwee MK, Miller HD *et al.* (2009) The toxicology of climate change: environmental contaminants in a warming world. *Environment international*, **35**, 971–86.

NSRF (2014) The Scottish Code for Conservation Translocations Best Practice Guidelines for Conservation Translocations in Scotland. *National Species Reintroduction Forum / SNH*.

O'Brien K (2012) Global environmental change II: From adaptation to deliberate transformation. *Progress in Human Geography*, **36**, 667–676.

Okabe A, Satoh T, Sugihara K (2009) A kernel density estimation method for networks , its computational method and a GIS based tool. *International Journal of Geographical Information Science*, 37–41.

Okkonen J, Kløve B (2010) A conceptual and statistical approach for the analysis of climate impact on ground water table fluctuation patterns in cold conditions. *Journal of Hydrology*, **388**, 1–12.

Oliver TH, Girardello M, Redhead R *et al.* (2013) Testing the effectiveness of climate change adaptation principles for biodiversity conservation. *Natural England Report*, 132.

Oliver TH, Morecroft MD (2014) Interactions between climate change and land use change on biodiversity: attribution problems, risks, and opportunities. *Wiley Interdisciplinary Reviews: Climate Change*, **5**, 317–335.

Ormerod SJ (2009) Climate change, river conservation and the adaptation challenge. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **613**, 609–613.

Ormerod SJJ, Durance I, Terrier A, Swanson AM (2010) Priority wetland invertebrates as conservation surrogates. *Conservation biology : the journal of the Society for Conservation Biology*, **24**, 573–82.

Owen GJ, Perks MT, Benskin CMH *et al.* (2012) Monitoring agricultural diffuse pollution through a dense monitoring network in the River Eden Demonstration Test Catchment, Cumbria, UK. *Area*, **44**, 443–453.

Palmer MA, Roy DB (2001) A method for estimating the extent of standing fresh waters of different trophic states in Great Britain. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **11**, 199–216.

Park SE, Marshall NA, Jakku E *et al.* (2012) Informing adaptation responses to climate change through theories of transformation. *Global Environmental Change*, **22**, 115–126.

Parr TW, Sier ARJ, Battarbee RW, Mackay A, Burgess J (2003) Detecting environmental change : science and society — perspectives on long-term research and monitoring in the 21st century. *The Science of the Total Environment*, **310**, 1–8.

Pearson RG, Dawson TP (2003) Predicting the impacts of climate change on the distribution of species: are bioclimate envelope models useful? *Global Ecology and Biogeography*, **12**, 361–371.

Phillips S, Anderson R, Schapire R (2006) Maximum entropy modeling of species geographic distributions. *Ecological Modelling*, **190**, 231–259.

Phillips A, Stolton S, Dudley N, Bishop K (2004) Use and Performance of the IUCN System of Management Categories for Protected Areas. *IUCN*, 1–195.

Pimbert MP, Pretty JN (1995) Parks, People and Professionals: Putting `Participation’ into Protected Area Management. *United Nationa Research Institute for Social Development*, **Discussion**.

Pittock J, Hansen LJ, Abell R (2009) Running dry : Freshwater biodiversity , protected areas and climate change. *Tropical Conservancy*, **9**, 30–38.

Poikane S, Portielje R, van den Berg M *et al.* (2014) Defining ecologically relevant water quality targets for lakes in Europe (A Strecker, Ed,). *Journal of Applied Ecology*, **51**, 592–602.

Polsky C, Neff R, Yarnal B (2007) Building comparable global change vulnerability assessments: The vulnerability scoping diagram. *Global Environmental Change*, **17**, 472–485.

Pooley SP, Mendelsohn JA, Milner-Gulland EJ (2014) Hunting down the chimera of multiple disciplinarity in conservation science. *Conservation biology : the journal of the Society for Conservation Biology*, **28**, 22–32.

Pratt JD, Mooney K a. (2013) Clinal adaptation and adaptive plasticity in Artemisia californica : implications for the response of a foundation species to predicted climate change. *Global Change Biology*, **19**, 2454–2466.

Prudhomme C, Dadson S, Morris D *et al.* (2012) Future Flows Climate: an ensemble of 1-km climate change projections for hydrological application in Great Britain. *Earth System Science Data*, **4**, 143–148.

Prudhomme C, Wilby RL, Crooks SM, Kay AL, Reynard NS (2010) Scenario-neutral approach to climate change impact studies: Application to flood risk. *Journal of Hydrology*, **390**, 198–209.

Pullin AS, Stewart GB (2006) Guidelines for systematic review in conservation and environmental management. *Conservation Biology*, **20**, 1647–56.

Rahel FJ (2007) Biogeographic barriers, connectivity and homogenization of freshwater faunas: it's a small world after all. *Freshwater Biology*, **52**, 696–710.

Rahel FJ, Bierwagen BG, Taniguchi Y (2008) Managing aquatic species of conservation concern in the face of climate change and invasive species. *Conservation Biology*, **22**, 551–61.

Rahel FJ, Olden JD (2008) Assessing the effects of climate change on aquatic invasive species. *Conservation Biology*, **22**, 521–33.

Raven PJ (2011) How will river conservation cope with the global economic downturn? Observations from an international conference. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **21**, 1–6.

Raven PJ, Holmes NTH, Vaughan IP, Dawson FH, Scarlett P (2010) Benchmarking habitat quality: observations using River Habitat Survey on near-natural streams and rivers in northern and western Europe. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **20**, S13–S30.

Raymond C, Peterson D, Rochefort R (2013) The North Cascadia Adaptation Partnership: A Science-Management Collaboration for Responding to Climate Change. *Sustainability*, **5**, 136–159.

Rennie AF, Hansom JD (2011) Sea level trend reversal: Land uplift outpaced by sea level rise on Scotland's coast. *Geomorphology*, **125**, 193–202.

Rosset V, Simaika JP, Arthaud F *et al.* (2013) Comparative assessment of scoring methods to evaluate the conservation value of pond and small lake biodiversity. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **23**, 23–36.

Rounsevell MDA, Reay DS (2009) Land use and climate change in the UK. *Land Use Policy*, **26**, S160–S169.

Rout TM, McDonald-Madden E, Martin TG *et al.* (2013) How to decide whether to move species threatened by climate change. *PloS one*, **8**, e75814.

Rowan JS (2010) *Developing a Lake Hydromorphology Typology for the UK*.

Rowan JS, Carwardine J, Duck RW *et al.* (2006) Development of a technique for Lake Habitat Survey (LHS) with applications for the European Union Water Framework Directive. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **16**, 637–657.

Rowan JS, Duck RW, Carwardine J *et al.* (2004) *Development of a Technique for Lake Habitat Survey (LHS) Phase 1*.

Rowan JS, Greig SJ, Armstrong CT, Smith DC, Tierney D (2012) Development of a classification and decision-support tool for assessing lake hydromorphology.

Environmental Modelling & Software, **36**, 86–98.

Rowan JS, Price LE, Fawcett CP, Young PC (2001) Reconstructing Historic Reservoir Sedimentation Rates Using Data-Based Mechanistic Modelling. *Phys. Chem. Earth (B)*, **26**, 77–82.

Rowland EL, Davison JE, Graumlich LJ (2011) Approaches to evaluating climate change impacts on species: a guide to initiating the adaptation planning process. *Environmental management*, **47**, 322–37.

Saloranta TM, Forsius M, Järvinen M, Arvola L (2009) Impacts of projected climate change on the thermodynamics of a shallow and a deep lake in Finland: model simulations and Bayesian uncertainty analysis. *Hydrology Research*, **40**, 234.

Sandbrook C, Adams WM, Büscher B, Vira B (2013) Social Research and Biodiversity Conservation. *Conservation biology : the journal of the Society for Conservation Biology*, **27**, 1487–1490.

Sayer CD, Davidson T a., Kelly A (2008) Ornamental lakes—an overlooked conservation resource? *Aquatic Conservation: Marine and Freshwater Ecosystems*, **18**, 1046–1051.

Schaich H, Bieling C, Plieninger T (2010) Linking Ecosystem Services with Cultural Landscape Research. *GAIA*, **4**, 269–277.

Schindler S, Sebesvari Z, Damm C *et al.* (2014) Multifunctionality of floodplain landscapes: relating management options to ecosystem services. *Landscape Ecology*, **29**, 229–244.

Schwenk WS, Donovan TM (2011) A multispecies framework for landscape conservation planning. *Conservation biology : the journal of the Society for Conservation Biology*, **25**, 1010–21.

Scott SE, Pray CL, Nowlin WH, Zhang Y (2012) Effects of native and invasive species on stream ecosystem functioning. *Aquatic Sciences*, **74**, 793–808.

Selman P (2009) Conservation designations-Are they fit for purpose in the 21st century? *Land Use Policy*, **26**.

Shaw MR, Klausmeyer K, Cameron DR, Mackenzie J, Roehrdanz P (2012) Economic Costs of Achieving Current Conservation Goals in the Future as Climate Changes. *Conservation Biology*, **26**, 385–396.

Shuter BJ, Finstad a. G, Helland IP, Zweimüller I, Hölker F (2012) The role of winter phenology in shaping the ecology of freshwater fish and their sensitivities to climate change. *Aquatic Sciences*, **74**, 637–657.

Sievanen L, Campbell LM, Leslie HM (2012) Challenges to interdisciplinary research in ecosystem-based management. *Conservation biology : the journal of the Society for Conservation Biology*, **26**, 315–23.

Simberloff D (1998) Flagships, umbrellas, and keystones: is single-species management passé in the landscape era? *Biological conservation*, **83**, 247–257.

van de Sind I (2012) Payments for Ecosystem Services in the Context of Adaptation to

Climate. *Ecology And Society*, **17**, 11–25.

Smit B, Wandel J (2006) Adaptation, adaptive capacity and vulnerability. *Global Environmental Change*, **16**, 282–292.

Smithers RJ, Cowan C, Harley M *et al.* (2008) England Biodiversity Strategy Climate Change Adaptation Principles. *DEFRA Published Report*, 1–16.

SNH (2008) Public Perceptions of Wild Places and Landscapes in Scotland. *SNH Commissioned Report No. 291*, **291**.

Snover AK, Mantua NJ, Littell JS *et al.* (2013) Choosing and Using Climate-Change Scenarios for Ecological-Impact Assessments and Conservation Decisions. *Conservation Biology*, **27**, 1147–1157.

Soranno PA, Cheruvelil KS, Webster KE *et al.* (2010) Using Landscape Limnology to Classify Freshwater Ecosystems for Multi-ecosystem Management and Conservation. *BioScience*, **60**, 440–454.

Soranno PA, Webster KE, Cheruvelil KS, Bremigan MT (2009) The lake landscape-context framework: linking aquatic connections, terrestrial features and human effects at multiple spatial scales. *Verh. Internat. Verein. Limnol.*, **30**, 695–700.

Soulé M (2013) The “new conservation”. *Conservation biology : the journal of the Society for Conservation Biology*, **27**, 895–7.

Soulsby C, Gibbins C, Wade AJ, Smart R, Helliwell RC (2002) Water quality in the Scottish uplands: a hydrological perspective on catchment hydrochemistry. *The Science of the total environment*, **294**, 73–94.

Spears BM, Carvalho L, Dudley B, May L (2013) Variation in chlorophyll a to total phosphorus ratio across 94 UK and Irish lakes: implications for lake management. *Journal of environmental management*, **115**, 287–94.

Spears BM, Carvalho L, Perkins R, Kirika A, Paterson DM (2012) Long-term variation and regulation of internal phosphorus loading in Loch Leven. *Hydrobiologia*, **681**, 23–33.

Staehr PA, Baastrup-Spohr L, Sand-Jensen K, Stedmon C (2012) Lake metabolism scales with lake morphometry and catchment conditions. *Aquatic Sciences*, **74**, 155–169.

Steffen W (2008) Working Group 1 report of the IPCC Fourth Assessment—An editorial. *Global Environmental Change*, **18**, 1–3.

Steudel B, Hector A, Friedl T *et al.* (2012) Biodiversity effects on ecosystem functioning change along environmental stress gradients. *Ecology letters*, **15**, 1397–405.

Strayer DL (2010) Alien species in fresh waters: ecological effects, interactions with other stressors, and prospects for the future. *Freshwater Biology*, **55**, 152–174.

Strayer DL, Beighley RE, Thompson LC *et al.* (2003) Effects of land cover on stream ecosystems: Roles of empirical models and scaling issues. *Ecosystems*, **6**, 407–423.

Strayer DL, Hillebrand H (2012) Eight questions about invasions and ecosystem functioning. *Ecology letters*, **15**, 1199–210.

Street RB, Steynor A, Bowyer P, Humphrey K (2009) Delivering and using the UK climate projections 2009. *Weather*, **64**, 227–231.

Sutherland WJ, Albon SD, Allison H *et al.* (2010) The identification of priority policy options for UK nature conservation. *Journal of Applied Ecology*, **47**, 955–965.

Tabor K, Williams JW (2010) Globally downscaled climate projections for assessing the conservation impacts of climate change. *Ecological applications : a publication of the Ecological Society of America*, **20**, 554–65.

Thackeray SJ, Henrys P a., Jones ID, Feuchtmayr H (2011) Eight decades of phenological change for a freshwater cladoceran: what are the consequences of our definition of seasonal timing? *Freshwater Biology*, no-no.

Thackeray SJ, Sparks TH, Frederiksen M *et al.* (2010) Trophic level asynchrony in rates of phenological change for marine, freshwater and terrestrial environments. *Global Change Biology*, **16**, 3304–3313.

The Scottish Government (2013) *2020 Challenge for Scotland's Biodiversity*. Edinburgh.

Thomas CD, Franco AMA, Hill JK (2006) Range retractions and extinction in the face of climate warming. *Trends in ecology & evolution*, **21**, 415–6.

Thomas CD, Gillingham PK (2015) The performance of protected areas for biodiversity under climate change. *Biological Journal of the Linnean Society*, **115**, 718–730.

Thomas CD, Gillingham PK, Bradbury RB *et al.* (2012) Protected areas facilitate species' range expansions. , **109**, 14063–14068.

Thomas SM, Griffiths SW, Ormerod SJ (2015) Adapting streams for climate change using riparian broadleaf trees and its consequences for stream salmonids. *Freshwater Biology*, **60**, 64–77.

Thompson RM, Beardall J, Beringer J, Grace M, Sardina P (2014) Moving beyond methods: the need for a diverse programme in climate change research (F Lloret, Ed,). *Ecology Letters*, **17**, 125-e2.

Thornton PK, Ericksen PJ, Herrero M, Challinor AJ (2014) Climate variability and vulnerability to climate change: a review. *Global Change Biology*, **20**, 3313–3328.

Tingley MW, Estes LD, Wilcove DS (2013) Climate change must not blow conservation off course. *Nature*, **500**, 271–272.

Tolonen KT, Hämäläinen H, Lensu A *et al.* (2014) The relevance of ecological status to ecosystem functions and services in a large boreal lake. *Journal of Applied Ecology*, **51**, 560–571.

Tomimatsu H, Sasaki T, Kurokawa H *et al.* (2013) Sustaining ecosystem functions in a changing world: a call for an integrated approach (I Steffan-Dewenter, Ed,).

Journal of Applied Ecology, n/a-n/a.

Tompkins EL, Adger WN (2004) Does Adaptive Management of Natural Resources Enhance Resilience to Climate Change? *Ecology And Society*, **9**, 10.

Trigal-Domínguez C, Fernández-Aláez C, García-Criado F (2009) Habitat selection and sampling design for ecological assessment of heterogeneous ponds using macroinvertebrates. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **19**, 786–796.

Trnka M, Olesen JE, Kersebaum KCC *et al.* (2011) Agroclimatic conditions in Europe under climate change. *Global Change Biology*, **17**, 2298–2318.

Tuck SL, Winqvist C, Mota F *et al.* (2014) Land-use intensity and the effects of organic farming on biodiversity: A hierarchical meta-analysis. *Journal of Applied Ecology*, **51**, 746–755.

Turnbull LA, Levine JM, Loreau M, Hector A (2013) Coexistence, niches and biodiversity effects on ecosystem functioning (JHR Lambers, Ed,). *Ecology Letters*, **16**, 116–127.

Turner MG (2005) LANDSCAPE ECOLOGY: What Is the State of the Science? *Annual Review of Ecology, Evolution, and Systematics*, **36**, 319–344.

UKCP (2009) United Kingdom Climate Change Projections. *MET Office*, **http://ukc**.

Varis O, Kuikka S (1999) Learning Bayesian decision analysis by doing: lessons from environmental and natural resources management. *Ecological Modelling*, **119**, 177–195.

Vaughan IP, Diamond M, Gurnell AM *et al.* (2009) Integrating ecology with hydromorphology : a priority for river science and management. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **125**, 113–125.

Vaughan IP, Ormerod SJ (2010) Linking ecological and hydromorphological data: approaches, challenges and future prospects for riverine science. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **20**, S125–S130.

Verburg PH, Neumann K, Nol L (2011) Challenges in using land use and land cover data for global change studies. *Global Change Biology*, **17**, 974–989.

Verpoorter C, Kutser T, Seekell DA, Tranvik LJ (2014) A global inventory of lakes based on high-resolution satellite imagery. *Geophysical Research Letters*, **41**, 1–7.

Vicente JR, Fernandes RF, Randin CF *et al.* (2013) Will climate change drive alien invasive plants into areas of high protection value? An improved model-based regional assessment to prioritise the management of invasions. *Journal of environmental management*, **131**, 185–95.

Villéger S, Grenouillet G, Brosse S (2013) Decomposing functional β-diversity reveals that low functional β-diversity is driven by low functional turnover in European fish assemblages. *Global Ecology and Biogeography*, **22**, 671–681.

Vogel C, Moser SC, Kasperson RE, Dabelko GD (2007) Linking vulnerability, adaptation, and resilience science to practice: Pathways, players, and partnerships. *Global Environmental Change*, **17**, 349–364.

Wagner T, Soranno PA, Webster KE, Chereruvelil KS (2011) Landscape drivers of regional variation in the relationship between total phosphorus and chlorophyll in lakes. *Freshwater Biology*, **56**, 1811–1824.

Walker B, Holling CS, Carpenter SR, Kinzig A (2004) Resilience, Adaptability and Transformability in Social – ecological Systems. *Ecology And Society*, **9**, 5.

Walther G-R, Roques A, Hulme PE *et al.* (2009) Alien species in a warmer world: risks and opportunities. *Trends in ecology & evolution (Personal edition)*, **24**, 686–93.

Wantzen KM, Rothhaupt K-O, Mörtl M *et al.* (2008) Ecological effects of water-level fluctuations in lakes: an urgent issue. *Hydrobiologia*, **613**, 1–4.

Warfe DM, Pettit NE, Magierowskil RH *et al.* (2013) Hydrological connectivity structures concordant plant and animal assemblages according to niche rather than dispersal processes. *Freshwater Biology*, **58**, 292–305.

Warren RJ, Bradford MA (2014) Mutualism fails when climate response differs between interacting species. *Global change biology*, **20**, 466–74.

Watson JEM, Cross MS, Rowland E *et al.* (2011) Planning for Species Conservation in a Time of Climate Change. In: *Climate Change - Research and Technology for Adaptation and Mitigation* (ed Blanco J), pp. 379–402. INTECH, Rijeka, Croatia.

Watson JEM, Dudley N, Segan DB, Hockings M (2014) The performance and potential of protected areas. *Nature*, **515**, 67–73.

Watson JEM, Evans MC, Carwardine J *et al.* (2010) The Capacity of Australia's Protected-Area System to Represent Threatened Species. *Conservation Biology*, 1–9.

Watson JEM, Fuller RA, Watson AWT *et al.* (2009) Wilderness and future conservation priorities in Australia. *Diversity and Distributions*, **15**, 1028–1036.

Watt MS, Stone JK, Hood IA, Manning LK (2011) Using a climatic niche model to predict the direct and indirect impacts of climate change on the distribution of Douglas-fir in New Zealand. *Global Change Biology*, **17**, 3608–3619.

Watts G, Battarbee RRW, Bloomfield JP *et al.* (2015) Climate change and water in the UK – past changes and future prospects. *Progress in Physical Geography*, **39**, 1–30.

Watts K, Eycott AE, Handley P *et al.* (2010) Targeting and evaluating biodiversity conservation action within fragmented landscapes: an approach based on generic focal species and least-cost networks. *Landscape Ecology*, **25**, 1305–1318.

Weatherhead EK, Howden NJK (2009) The relationship between land use and surface water resources in the UK. *Land Use Policy*, **26**, S243–S250.

Webber BL, Scott JK (2012) Rapid global change: implications for defining natives and aliens. *Global Ecology and Biogeography*, **21**, 305–311.

Webster KE, Kratz TK, Bowser CJ, Magnuson JJ, Rose WJ (1996) The influence of landscape position on lake chemical responses to drought in northern Wisconsin. *Limnology and Oceanography*, **41**, 977–984.

Webster KE, Soranno PA, Baines SB *et al.* (2000) Structuring features of lake districts: landscape controls on lake chemical responses to drought. *Freshwater Biology*, **43**, 499–515.

Weijters MJ, Janse JH, Alkemade R, Verhoeven JTA (2009) Quantifying the effect of catchment land use and water nutrient concentrations on freshwater river and stream biodiversity. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **19**, 104–112.

Westgate MJ, Likens GE, Lindenmayer DB (2013) Adaptive management of biological systems: A review. *Biological Conservation*, **158**, 128–139.

Whitehead AL, Kujala H, Ives CD *et al.* (2014) Integrating Biological and Social Values When Prioritizing Places for Biodiversity Conservation. *Conservation Biology*, **28**, 992–1003.

Whitehead PG, Wilby RL, Battarbee RW, Kernan M, Wade AJ (2009) A review of the potential impacts of climate change on surface water quality. *Hydrological Sciences Journal*, **54**, 101–123.

Whitman A, Cutko A, DeMaynadier P *et al.* (2013) Vulnerability of Habitats and Priority Species. *MANOMET Centre for Conservation Sciences*, **13**, 100.

Wiens JA (2002) Riverine landscapes: taking landscape ecology into the water. *Freshwater Biology*, **47**, 501–515.

Wiens JA (2012) Is landscape sustainability a useful concept in a changing world? *Landscape Ecology*, **28**, 1047–1052.

Wilby RL, Orr HG, Hedger M, Forrow D, Blackmore M (2006) Risks posed by climate change to the delivery of Water Framework Directive objectives in the UK. *Environment International*, **32**, 1043–1055.

Wilby RL, Orr H, Watts G *et al.* (2010) Evidence needed to manage freshwater ecosystems in a changing climate: turning adaptation principles into practice. *The Science of the total environment*, **408**, 4150–64.

Wilby RL, Wood PJ (2012) Introduction to adapting water management to climate change: putting our science into practice. *Area*, **44**, 394–399.

Willby NJ, Pitt JA, Phillips G (2009) The ecological classification of UK lakes using aquatic macrophytes. *UK Environment Agency Science Reports*, **Project SC**.

Williams SE, Shoo LP, Isaac JL, Hoffmann A a, Langham G (2008) Towards an integrated framework for assessing the vulnerability of species to climate change. *PLoS biology*, **6**, 2621–6.

Winder M, Schindler DE (2004a) Climate change uncouples trophic interactions in an aquatic ecosystem. *Ecology*, **85**, 2100–2106.

Winder M, Schindler DE (2004b) Climatic effects on the phenology of lake processes.

Global Change Biology, **10**, 1844–1856.

Wise RM, Fazey I, Stafford Smith M *et al.* (2014) Reconceptualising adaptation to climate change as part of pathways of change and response. *Global Environmental Change*, **28**, 325–336.

Wolock DM, Mccabe GJ (1999) Estimates of runoff using water balance and atmospheric general circulation models. *Journal Of The American Water Resources Association*, **35**, 1341–1350.

Wood PJ, Hannah DM, Sadler JP (2007) Ecohydrology and Hydroecology : An Introduction. In: (eds Wood PJ, Hannah DM, Sadler JP), pp. 1–6. John Wiley & Sons.

Woodward G, Perkins DM, Brown LE (2010) Climate change and freshwater ecosystems: impacts across multiple levels of organization. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **365**, 2093–2106.

Wright KB (2006) Researching Internet-Based Populations: Advantages and Disadvantages of Online Survey Research, Online Questionnaire Authoring Software Packages, and Web Survey Services. *Journal of Computer-Mediated Communication*, **10**, 00–00.

Zahran S, Brody SD, Vedlitz A, Grover H, Miller C (2008) Vulnerability and capacity: explaining local commitment to climate-change policy. *Environment and Planning C: Government and Policy*, **26**, 544–562.

Zerger A (2002) Examining GIS decision utility for natural hazard risk modelling. *Environmental Modelling & Software*, **17**, 287–294.

Zhang L, Dawes WR, Walker GR (2001) Response of mean annual evapotranspiration to vegetation changes at catchment scale. *Journal of Water Resources Research*, **37**, 701–708.

Zimmerer KS (2006) Cultural ecology: at the interface with political ecology-the new geographies of environmental conservation and globalization. *Progress in Human Geography*, **1**, 63–78.